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TITLE: TBI Assessment of Readiness Using a Gait Evaluation Test (TARGET): Development of a Portable mTBI Screening Device

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

In this annual report, we outline the ongoing data collection for our Major Tasks. We have completed 99% of our data collection on healthy civilians and 100% of our data collection on healthy military participants. We have completed 30% of our data collection on civilians with mTBI and have connected with key personnel at NICoE to start our data collection on military personnel with mTBI. We also outline the publications and conference presentations that were completed during this reporting period. We were recently granted an Extension Without Funds (EWOF) for 12 months, during which time we anticipate completing the data collection and analyses outlined in our proposal.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:

a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON USAMRMC
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1. **INTRODUCTION:** Narrative that briefly (one paragraph) describes the subject, purpose and scope of the research.

> With up to 320,000 service members sustaining some form of traumatic brain injury (TBI) over the past 14 years, the lack of an objective measurement tool for evaluation and monitoring of TBI is of great concern to the military. The NeuroCom® Sensory Organization Test (SOT) is the current 'gold standard' for assessing mTBI-related motor impairments. However, the equipment's size and logistical footprint makes it impractical for field deployment. This study seeks to determine the validity and reliability of an Android device-based mTBI (mild traumatic brain injury) screening test app for assessing motor function. The app, AccWalker, utilizes the smartphone's accelerometer and orientation metrics in order to assess a person's functional motor ability. The study will seek to establish test-retest and inter-rater reliability of the app within a healthy civilian population, concurrent validity with the SOT, BESS, CB&M test (three currently used assessments) in a healthy civilian population, and predictive validity to discriminate between healthy individuals and those with clinically confirmed mTBI in both a civilian and military population.

2. **KEYWORDS:** Provide a brief list of keywords (limit to 20 words).

> mild traumatic brain injury (mTBI), concussion, AccWalker, Sensory Organization Test (SOT), Balance Error Scoring System (BESS), Community Balance & Mobility Scale (CB&M), Military Acute Concussion Evaluation (MACE), smartphone, TARGET, military, civilian, validity, reliability

3. **ACCOMPLISHMENTS:** The PI is reminded that the recipient organization is required to obtain prior written approval from the awarding agency Grants Officer whenever there are significant changes in the project or its direction.

What were the major goals of the project?
List the major goals of the project as stated in the approved SOW. If the application listed milestones/target dates for important activities or phases of the project, identify these dates and show actual completion dates or the percentage of completion.

- Pre-task – Institutional Review Board and Human Research Protection Office Application, timeline: 1-2 months
    - Milestone: IRB and HRPO approval will be obtained at UNCG, 100%, completion date: 04/22/2016
    - Milestone: IRB and HRPO approval will be obtained at Temple, 100%, completion date: 04/22/2016
    - Milestone: IRB and HRPO approval will be obtained at NICoE, 25%
- Major Task 1 – Normative data collection on healthy civilians, timeline: 3-9 months
    - Milestone: 100 healthy civilians will complete the TARGET, MACE, NeuroCom's SOT, and the Balance Error Scoring System (BESS), which will serve as our normative data
        - UNCG & Temple, 99%
- Major Task 2 – mTBI data collection on civilians, timeline: 3-9 months
    - Milestone: 50 civilians with mTBI will complete the TARGET, MACE, NeuroCom's SOT, and BESS
        - UNCG & Temple, 30%
- Major Task 3 – Derive normative military values from previously collected data, timeline: 9-15 months
    - Milestone: data from 25 healthy military personnel who previously completed the TARGET for a separate project will be analyzed to derive military-specific norm references for reliable change index calculations
        - Percent complete: 100%
        - Although only 25 military personnel were included in the SOW, data from 90 military personnel were reported in a recent manuscript (published in the journal *Military Medicine*
- Major Task 4 – mTBI data collection on military personnel, timeline: 15-21 months
    - Milestone: 25 military personnel with mTBI from NICoE will complete the TARGET to determine the clinical utility of the TARGET as an mTBI screen in military populations
        - Percent complete: 0%
- Major Task 5 – data analysis/software optimization, timeline: 17-24 months
    - Milestone: RCI and ROC curves will be calculated on a number of different variability metrics, 0%
    - Milestone: Optimized AccWalker that provides a simple red light indicator when neurological impairment from mTBI is detected in the stepping-in-place task, 0%

What was accomplished under these goals?
For this reporting period describe: 1) major activities; 2) specific objectives; 3) significant results or key outcomes, including major findings, developments, or conclusions (both positive and negative); and/or 4) other achievements. Include a discussion of stated goals not met. Description shall include pertinent data and graphs in sufficient detail to explain any significant results achieved. A succinct description of the methodology used shall be provided. As the project progresses to completion, the emphasis in reporting in this section should shift from reporting activities to reporting accomplishments.

- **TIMELINE OF PROGRESS:**
  - **Beginning of May 2016 to mid-February 2017:**
    - Continued data collection at UNCG and Temple for both healthy and concussed civilians
    - Various user-interface and metric-calculation updates made to the app
    - Attended several conferences to present initial analyses, including:
      - North American Society for the Psychology of Sport and Physical Activity, June 2016
      - Military Health System Research Symposium, August 2016
      - American Society of Biomechanics, August 2016
      -
    - Revised manuscript submitted to the peer-reviewed journal Military Medicine, was accepted on 10/14/2016
      - Rhea, C.K., Kuznetsov, N.A., Ross, S.E., Long, B., Jakiela, J.T., Bailie, J.M., Yanagi, M.A., Haran, F.J., Wright, W.G., Robins, R.K., Sargent, P.D., & Duckworth, J.L. (2017). Development of a portable tool for screening neuromotor sequelae from repetitive low-level blast exposure. *Military Medicine*, 182(3/4), 147-154
  - **Mid-February 2017 to end of March 2017:**
    - FDA issue at UNCG:
      - In mid-February, we received word from our UNCG IRB committee that we were to cease all data collection for the study. The reasoning was that a member had recently attending an FDA guidelines for research informational session and had some questions regarding the status of our smartphone as an investigational device vs purely a data collection tool. Their initial impression was that our device qualified as an investigational device that needed to be registered with the FDA to receive exemption status. We were asked by the IRB to fill out FDA documentation for registering the device/applying for exemption. After completing the paperwork, Dr. Rhea spoke with an FDA contact only to then find out that the FDA did not think our app fell under their requirements and that ultimately, that determination is made by our local IRB committee. Our university IRB then said they would review this new information and decide at their monthly meeting on March 22nd, 2017. We presented our case (that our app was purely being used for data collection and that no diagnosis could be determined from it) and it was decided that we did not have to apply to the FDA, but that we needed to include a few pieces of information in our consent form. They asked we refer to the app/smartphone as an investigational device and state that the FDA may review the deidentified data/records when applicable.
      - Had to cancel the collections for the remaining 5 healthy civilians and 2 concussed civilians, given this issue. When contacted again at the end of March, they were uninterested in participating/never responded.
    - Concussed civilian recruitment: Given our difficulties in finding concussed participants at UNCG and Temple, we sought to expand our conclusion criteria for this population as well as reach out to several local universities
      - Concussed inclusion criteria expanded to 120 days post-concussion
      - Were unable to implement these changes to the IRB until after the FDA issue was resolved, given all recruitment and collection was ordered to halt
    - Concussed military recruitment—NICoE update: Dr. Rhea met with Dr. Lou French, Deputy Director for Operations for the National Intrepid Center of Excellence (NICoE), on 3/8/2017 while attending the National Capital Area TBI Research Symposium. They discussed the most efficient way to collect data within the current NICoE data collection structure. Dr. French said he would think about the best way to integrate our project within the NICoE. Dr. Rhea will follow-up with Dr. French to begin the paperwork needed to collect data at NICoE.

- o Attended the Human Movement Science Symposium in Chapel Hill, NC and presented some of our work on this project
  - o Received 1-year no-cost extension to finish up concussed data collection and all analyses
- **Month of April 2017:**
  - o Started/continued data collection at UNCG and Temple for both healthy and concussed civilians
    - ▪ Current total number of healthy and concussed participant tested:
      - • UNCG (58 total)
        - o <u>Healthy</u> – 49 participants (27 females, 22 males)
        - o <u>Concussed</u> – 9 participants (8 females, 1 male)
      - • Temple: (56 total)
        - o <u>Healthy</u> – 50 participants (23 females, 27 males)
        - o <u>Concussed</u> – 6 participants (1 female, 5 males)
  - o Remaining healthy male scheduled for collection at UNCG in June
  - o FITBIR:
    - ▪ Our FITBIR contact is cross-mapping our current demographics form with the form they use, to ensure we can add our additional elements to the database when necessary
    - ▪ We discovered that our demographics form was missing a couple pieces of information needed to generate true GUIDs on the FITBIR site (middle name, country of birth). We found out that we can generate pseudo-GUIDs, if necessary. At that point, we discussed the possibility of tracking down previous participants (and whether the IRB would approve it), and decided that it wasn't feasible to do so.

- **ACCOMPLISHMENTS RELATIVE TO EACH MAJOR TASK**
  - **Pre-task – Institutional Review Board and Human Research Protection Office Application, timeline: 1-2 months**
    - o UNCG: Approval was received in previous annual reporting year and continuing approval was received in this annual reporting year
    - o Temple: Approval was received in previous annual reporting year and continuing approval was received in this annual reporting year
    - o NICoE: Dr. Rhea met with Dr. Lou French from NICoE on 3/8/2017 to discuss moving forward with IRB and HRPO paperwork for this study.
  - **Major Task 1 – Normative data collection on healthy civilians, timeline: 3-9 months**
    - o **Milestone:** 100 healthy civilians will complete the TARGET, MACE, NeuroCom's SOT, and the Balance
      - ▪ We have continued collecting data on healthy civilians during this reporting period and we are 99% complete with this major task.
    - o **Significant results:**
      - ▪ Data from Major Task 1 were used to derive the reliability and validity of the TARGET task
      - ▪ A manuscript describing our reliability and validity has been developed and will be submitted in the peer-reviewed journal *Annals of Biomedical Engineering* in June 2017
      - ▪ Significant results include:
        - • Experiments 1 and 2 compared internal Android OS smartphone orientation detection algorithms to a biomechanics laboratory motion capture system using a pendulum [i.e., non-biological movement (Figures 1 & 2)] and a human stepping [i.e., biological movement (Figure 3)].
          - o Smartphone sensors provided valid measurements of movement timing and amplitude, as well as their variability (Figures 1 & 3).
          - o However, sensor firmware version and Android OS version significantly affected the quality of measurement (Figure 2).
        - • Experiment 3 established high test-retest reliability of a stepping-in-place protocol in three different sensory probing conditions (eyes open, no-vision, head shake) using temporal and kinematic variability metrics extracted from the thigh and trunk orientation signal in a sample of healthy young adults (Tables 1 and 2, Figure 4).
      - ▪ Collectively, these experiments showed that our smartphone application is a valid and reliable way to measure dynamic balance, which could provide an objective way to assess neuromotor function after head trauma or in other populations where balance dysfunction may arise.
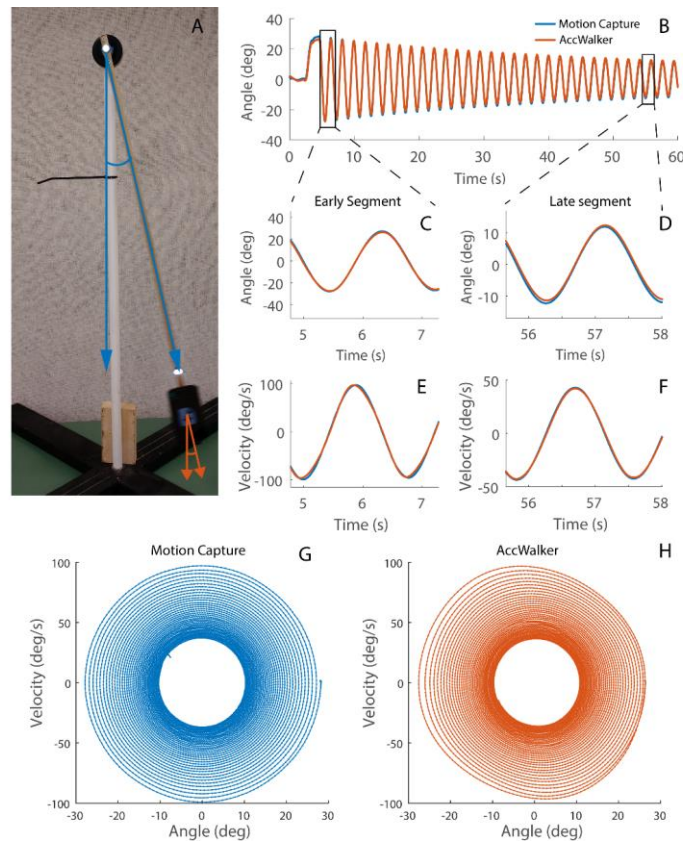
Figure 1. Testing of the AccWalker to detect pendulum angle in comparison to Qualisys motion capture system.
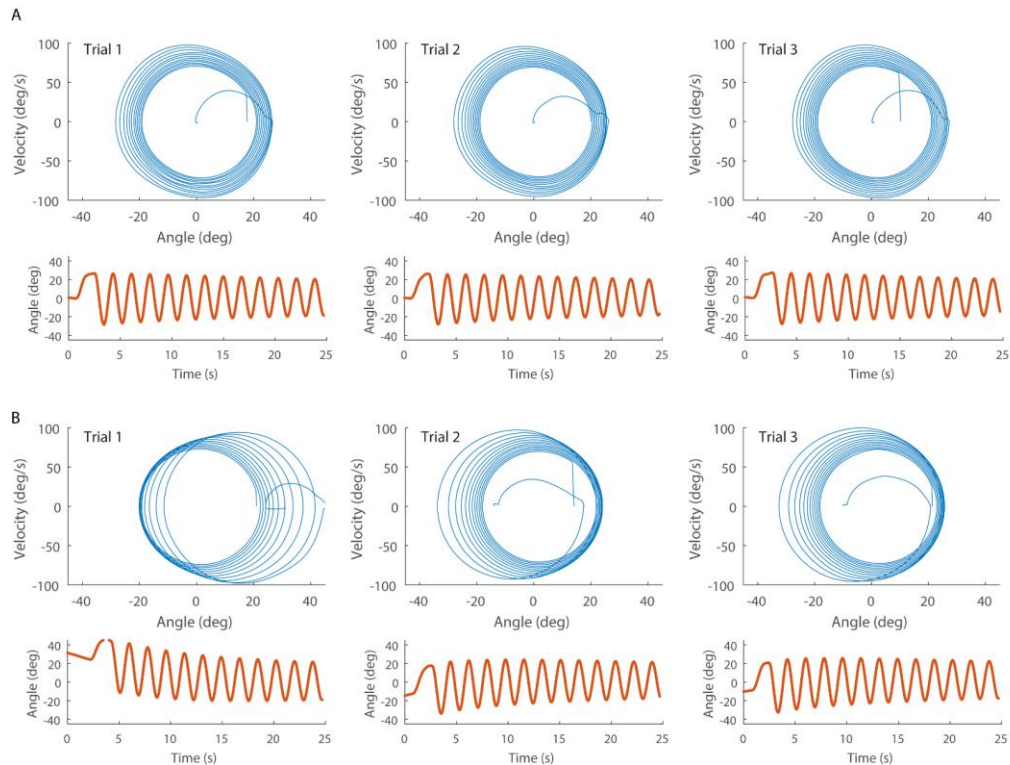

Figure 2. Performance of the AccWalker when running on Android OS 4.4.4 (top panels) vs. running on Android 5.1 (bottom panels). The inset in orange shows the time series of the pendulum angle corresponding to the phase space in the figure—drift is clearly evident in the bottom panels.
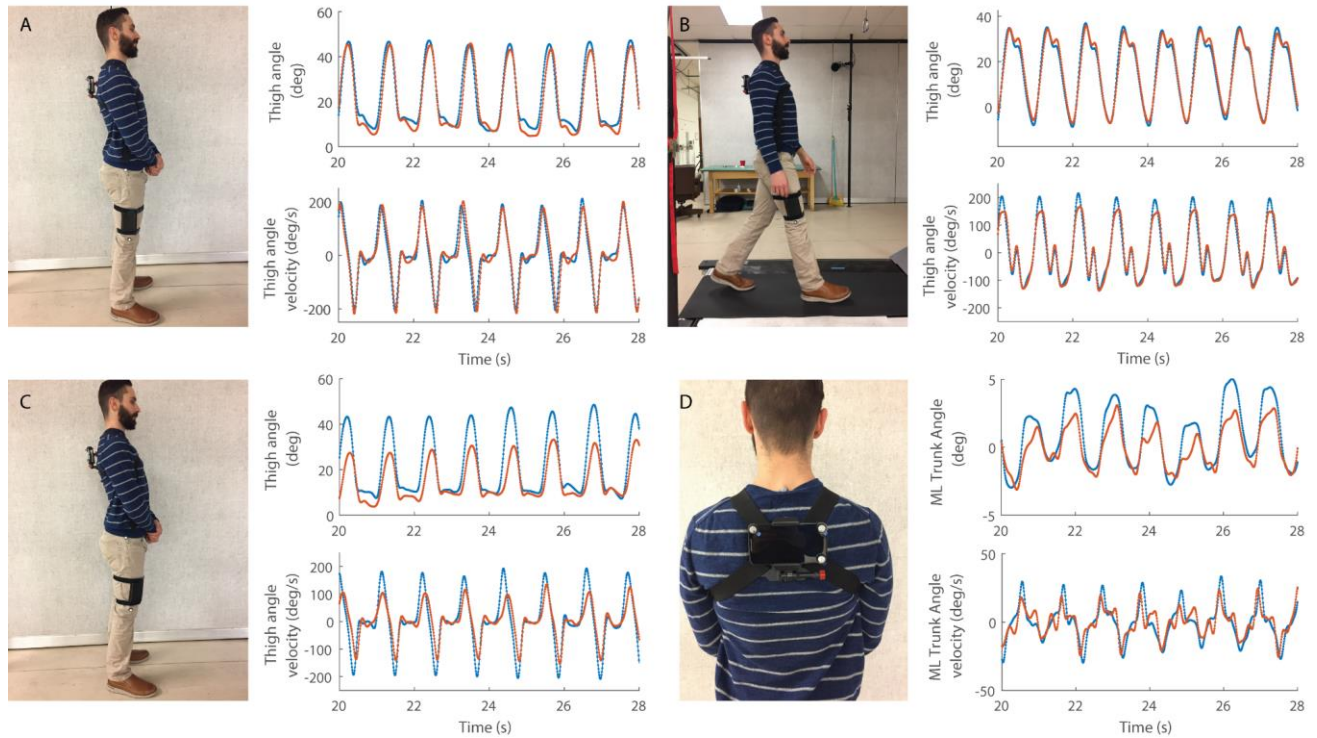
Figure 3. Thigh angle (A) and velocity (B) recorded by the motion capture system (blue) and the AccWalker (orange) during the stepping-in-place task. Greater thigh angle represents greater thigh flexion.

Table I

Average thigh and trunk metrics calculated from 3D motion capture and AccWalker, and the results of Bland-Altman LOA test when the phone was properly placed on the leg (see Figure 3A).

		Motion capture		AccWalker		95% LOA				
	Unit	Mean	SD	Mean	SD	Bias	SD	Lower	Upper	SD LOA/SD
Temporal metrics										
Timing accuracy	%	-0.67	3.44	-0.69	3.43	-0.02	0.05	-0.13	0.09	1.57%
Mean stride time	s	1.14	0.04	1.14	0.04	0.00	0.00	0.00	0.00	2.53%
CV stride time	%	2.06	0.32	2.07	0.32	0.01	0.07	-0.11	0.15	21.88%
ACF1	a.u.	0.31	0.16	0.30	0.15	-0.01	0.06	-0.13	0.11	37.62%
Pace drift	s	0.04	0.02	0.04	0.02	0.00	0.00	0.00	0.00	4.60%
Spatial metrics										
Peak thigh SD	deg	1.99	0.57	2.11	0.55	0.12	0.08	-0.05	0.28	14.04%
Peak thigh SD/ROM	%	4.55	0.92	4.56	0.91	0.01	0.17	-0.33	0.34	18.13%
Thigh ROM	deg	44.03	8.54	46.63	8.57	2.65	1.36	-0.07	5.37	15.95%
Peak Lift Vel SD	deg/s	11.90	2.95	10.91	2.30	-0.99	1.21	-3.41	1.43	41.05%
Peak Return Vel SD	deg/s	12.23	2.69	13.98	3.63	1.76	1.32	-0.88	4.39	48.98%
Trunk: Spatial metrics										
ML SD	deg	1.41	0.43	1.61	0.50	0.20	0.39	-0.57	0.97	88.78%
ML velocity SD	deg/s	8.24	2.53	9.88	2.57	1.64	1.93	-2.20	5.48	76.44%

Note. SD – standard deviation, Bias – average difference between the 3D motion capture and AccWalker, SD LOA – standard deviation of the difference between the 3D motion capture and AccWalker, SD LOA/SD – ratio of the SD LOA to SD of the 3D motion capture (expressed as percentage).

Table II

Average thigh and trunk metrics calculated from 3D motion capture and AccWalker, and the results of Bland-Altman LOA test when the phone was placed more anteriorly on the leg (see Figure 3C).

	Unit	Motion capture		AccWalker		95% LOA				
		Mean	SD	Mean	SD	Bias	SD	Lower	Upper	SD LOA/SD
Temporal metrics										
Timing accuracy	%	-1.93	3.44	-1.93	3.43	0.00	0.05	-0.10	0.10	1.46%
Mean stride time	s	1.13	0.04	1.13	0.04	0.00	0.00	0.00	0.00	1.46%
CV stride time	%	1.88	0.30	1.98	0.33	0.10	0.13	-0.16	0.37	45.00%
ACF1	a.u.	0.18	0.14	0.11	0.11	-0.07	0.10	-0.26	0.13	70.01%
Pace drift	s	0.02	0.01	0.02	0.01	0.00	0.00	0.00	0.00	10.22%
Spatial metrics										
Peak thigh SD	deg	1.98	0.57	1.91	0.60	-0.08	0.21	-0.50	0.34	36.82%
Peak thigh SD/ROM	%	4.93	1.24	6.78	2.15	1.85	1.40	-0.95	4.64	112.56%
Thigh ROM	deg	40.56	6.85	29.09	7.15	-11.47	4.68	-20.83	-2.11	68.33%
Peak Lift Vel SD	deg/s	12.52	3.19	10.78	2.53	-1.74	1.66	-5.07	1.59	52.18%
Peak Return Vel SD	deg/s	11.31	3.49	11.27	4.48	-0.04	1.44	-2.92	2.83	41.22%

Note. SD – standard deviation, Bias – average difference between the 3D motion capture and AccWalker, SD LOA – standard deviation of the difference between the 3D motion capture and AccWalker, SD LOA/SD – ratio of the SD LOA to SD of the 3D motion capture (expressed as percentage).

Table III

ICC(2,k) and SEM values for each variable and condition.

	Unit	ICC(2,k)			SEM		
		Eyes Open	No-Vision	Head Shake	Eyes Open	No-Vision	Head Shake
Temporal metrics							
Mean stride time	s	0.80*	0.80	0.81	0.02	0.02	0.03
CV stride time	%	0.77	0.82	0.81*	0.34	0.27	0.31
ACF1	a.u.	0.49*	0.78	0.44	0.16	0.10	0.15
Pace drift	s	0.23	0.47	0.54	0.02	0.02	0.02
Spatial metrics							
Peak thigh SD	deg	0.82	0.73*	0.89*	0.32	0.46	0.36
Thigh ROM	deg	0.90	0.92	0.94	4.10	3.82	3.23
Peak Lift Vel SD	deg/s	0.82	0.77*	0.88*	1.39	1.97	1.78
Peak Return Vel SD	deg/s	0.90	0.85*	0.89*	1.64	2.27	2.23
Trunk: Spatial metrics							
ML SD	deg	0.59	0.89	0.94*	0.33	0.17	0.16
ML velocity SD	deg/s	0.64	0.90	0.96*	1.74	0.94	0.86

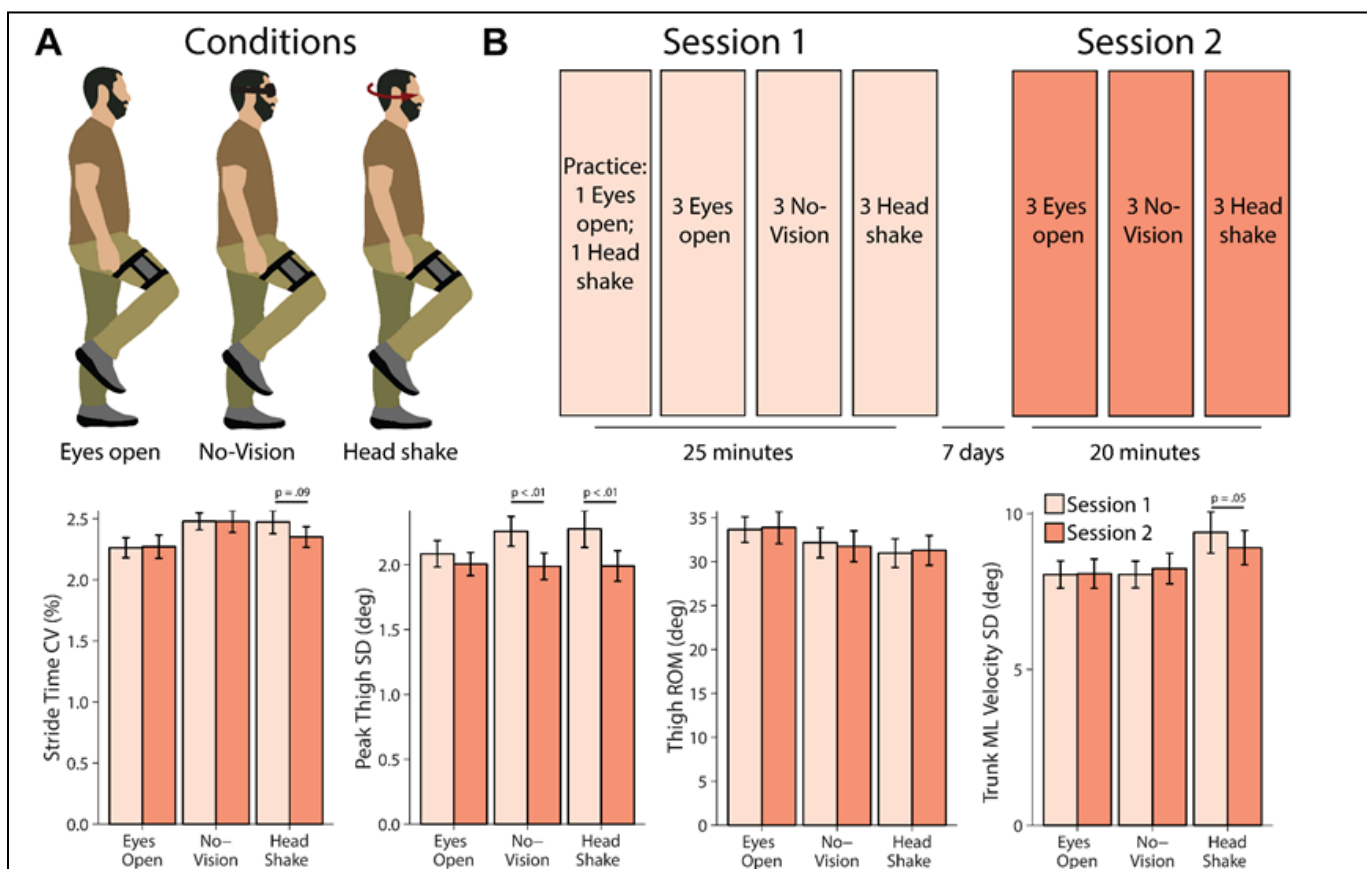*Note.* * signifies presence of a practice effect.

Figure 4. (A) Experimental conditions, (B) study design, (C) changes in the dependent measures for each sensory condition and session.

- **Major Task 2 – mTBI data collection on civilians, timeline: 3-9 months**
  - **Milestone:** 50 civilians with mTBI will complete the TARGET, MACE, NeuroCom's SOT, and BESS
    - We have continued collecting data on concussed civilians during this reporting period and we are 30% complete with this major task.
  - **Significant results:**
    - Although we are still collecting data for Major Task 2, we have used an innovative analysis to called Adaptive Fractal Analysis to evaluate multiple scales of postural control during the SOT in healthy and concussed individuals.
    - We used a cross-sectional design with four groups of active young adults: no concussion history (N = 80), acute concussion (N = 6, median = 4 days, range = 3 to 9 days), recent concussion (N = 5, median = 30 days, 16 to 37 days), and long-term history of concussion (N = 7, median = 4 yrs, range = 1 to 14 yrs).
    - These data were presented at the *2017 Human Movement Science & Biomechanics Research Symposium*
    - Significant results include:
      - We found alterations of postural control of the concussed participants at the fast time scales (30-170 ms), but no group differences at the longer time scales (.25 s - 2.5 s) (Figure 5).
      - These results indicate that the fast scale of COP dynamics (30-170 ms) is more sensitive to the effects of concussion than the intermediate scale of COP dynamics. The results also indicate that balance symptoms of concussion resolve within 9-16 days after the injury.
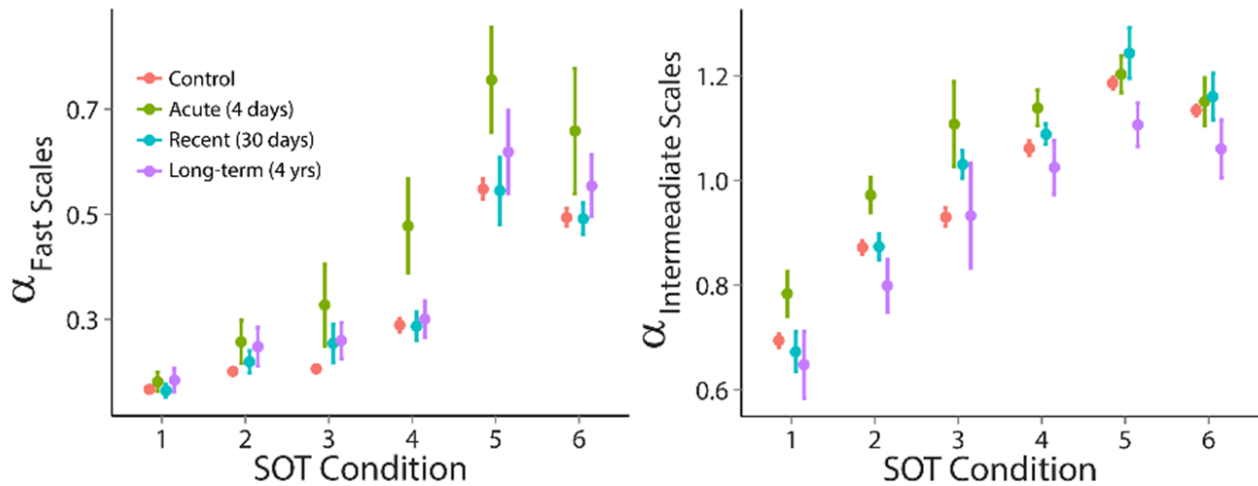
Figure 5. Scaling exponent (α) for the fast and intermediate scales during the SOT. Error bars indicate standard error of the mean.

- We have also examined the convergent validity of our stepping-in-place protocol in comparison to Balance Error Scoring System (BESS), Sensory Organization Test (SOT), and Community Balance and Mobility Scale (CB&M), as these tests have been previously used to characterize balance deficits after a concussion.
- These data will be presented at the *2017 North American Society for Psychology in Sport and Physical Activity*
- Significant results include:
  - Moderate correlations between step timing variability during the stepping in place task and BESS, SOT, CB&M, indicating that our objective test has convergent validity with these widely-used tests (Figure 6).
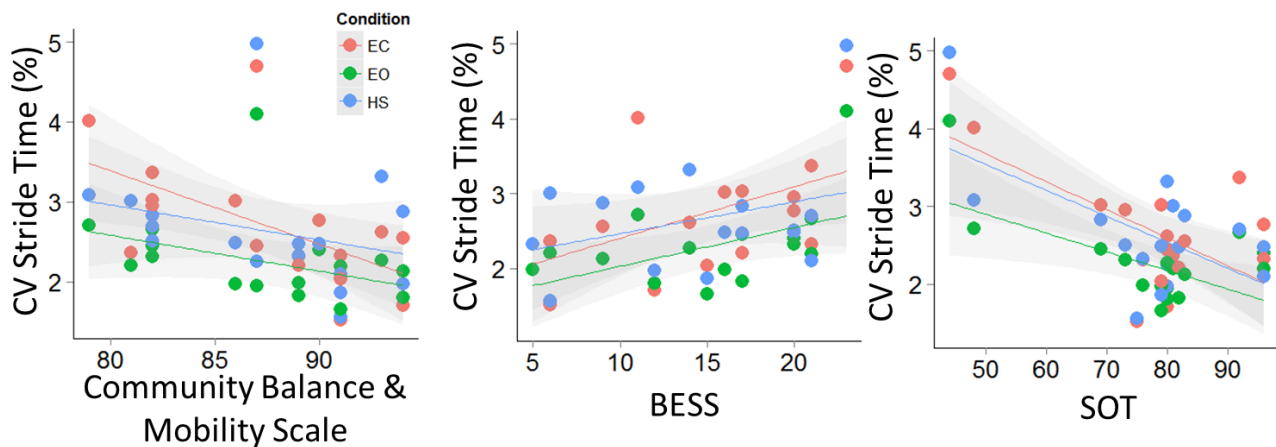

Figure 6. Stride time variability from the TARGET protocol correlated with the Community Balance and Mobility Scale and BESS, indicating clinical utility of the metric.

- Lastly, we have compared healthy and concussed performance on the stepping task.
- These data will be presented at the *2017 International Society for Posture and Gait Research (ISPGR)*
- We examined thigh movement variability and range of motion (ROM) during a dynamic balance task in participants who received a concussion in the within the last 40 days compared to a non-concussed population.

- We found an increase in movement timing variability after concussion and decreased ROM in the eyes closed condition, showing that neural control is altered for up to 40 days after a concussion (Figure 7).
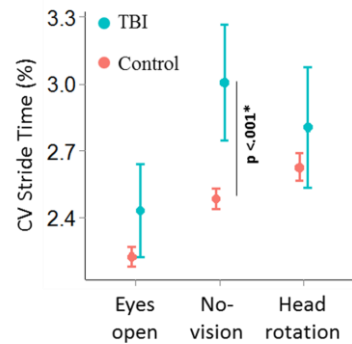

Figure 7. Greater stride time variability in individuals with recent TBI, especially in the no-vision condition – altered proprioceptive control

- **Major Task 3 – Derive normative military values from previously collected data, timeline: 9-15 months**
  - **Milestone:** Data from 25 healthy military personnel who previously completed the TARGET for a separate project will be analyzed to derive military-specific norm references for reliable change index calculations
    - We have completed this task
  - **Significant results:**
    - These data were published in *Military Medicine*. Our manuscript was accepted in 10/14/2017.
    - Active-duty United States Navy personnel (N = 59) performed a stepping-in-place task prior to repetitive LLB exposure (heavy weapons training), and again immediately after, 24 hours after, and 72-96 hours after the completion of the training (Figure 8).
    - The AccWalker app revealed that there are changes in neuromotor functioning after low-level blast (LLB) exposure (slower self-selected movement pace and increased stride time variability) in participants who experienced neurocognitive decline (Figure 8).
    - These data suggest that neurocognitive and neuromotor decline can occur after repeated LLB exposure.
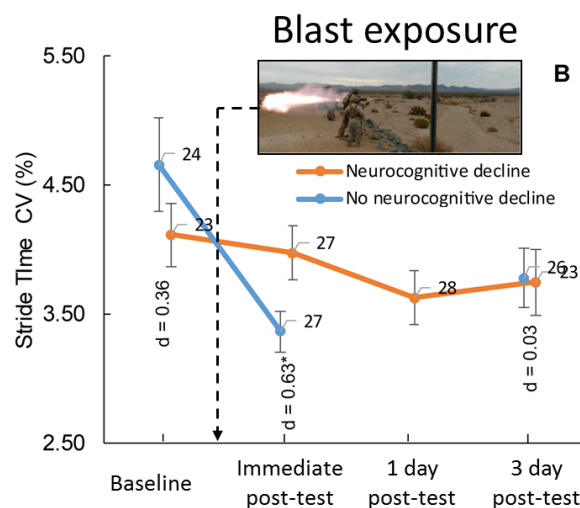

Figure 8. After being exposed to blasts, the neurocognitive decline group showed relatively slower and more variable stride time pattern than the group without neurocognitive decline

- **Major Task 4 – mTBI data collection on military personnel, timeline: 15-21 months**
  - **Milestone:** 25 military personnel with mTBI from NICoE will complete the TARGET to determine the clinical utility of the TARGET as an mTBI screen in military populations
    - We have met with Dr. French at NICoE to discuss integrating our project into their data collection process.
- **Major Task 5 – data analysis/software optimization, timeline: 17-24 months**
  - **Milestone:** RCI and ROC curves will be calculated on a number of different variability metric
  - **Milestone:** Optimized AccWalker that provides a simple red light indicator when neurological impairment from mTBI is detected in the stepping-in-place task
    - This task will be completed once all data has been collected.

What opportunities for training and professional development has the project provided?
If the project was not intended to provide training and professional development opportunities or there is nothing significant to report during this reporting period, state "Nothing to Report."

Describe opportunities for training and professional development provided to anyone who worked on the project or anyone who was involved in the activities supported by the project. "Training" activities are those in which individuals with advanced professional skills and experience assist others in attaining greater proficiency. Training activities may include, for example, courses or one-on-one work with a mentor. "Professional development" activities result in increased knowledge or skill in one's area of expertise and may include workshops, conferences, seminars, study groups, and individual study. Include participation in conferences, workshops, and seminars not listed under major activities.

Training
- Grant Writing Course at UNCG (KIN 798: Doctoral Seminar in Grant Writing) audited by Nikita Kuznetsov, Fall semester 2016

Professional Development
- North American Society for Psychology in Sport and Physical Activity (NASPSPA) conference attended by Chris Rhea, Geoff Wright, Nikita Kuznetsov, Becca Robins, and Jason Jakiela, June 2016
- Military Health System Research Symposium (MHSRS) attended by Chris Rhea, Geoff Wright, Nikita Kuznetsov, Becca Robins, and Jason Jakiela, August 2016
- American Society of Biomechanics (ASB) attended by Chris Rhea, Nikita Kuznetsov, and Jason Jakiela, August 2016
- Defense Centers of Excellence for Psychological Health and Traumatic Brain Injury Summit attended by Chris Rhea, Nikita Kuznetsov, and Jason Jakiela, September 2016
- 4th Matthew Gfeller Neurotrauma Symposium attended by Nikita Kuznetsov, March 2017
- Human Movement Science Symposium attended by Chris Rhea, Nikita Kuznetsov, and Jason Jakiela, March 2017

How were the results disseminated to communities of interest?
If there is nothing significant to report during this reporting period, state "Nothing to Report."

Describe how the results were disseminated to communities of interest. Include any outreach activities that were undertaken to reach members of communities who are not usually aware of these project activities, for the purpose of enhancing public understanding and increasing interest in learning and careers in science, technology, and the humanities.

Nothing to Report

What do you plan to do during the next reporting period to accomplish the goals?
If this is the final report, state "Nothing to Report."

Describe briefly what you plan to do during the next reporting period to accomplish the goals and objectives.

- Major Task 1: collect final participant to complete healthy civilian group
- Major Task 2: Continue to check in with student health center, athletic training office, and campus rec centers to see if they have had any recent concussions
- Major Task 3: Nothing to Report – data collection complete and manuscript is published in *Military Medicine*
- Major Task 4: Follow-up with Dr. French at NICoE, finalize IRB and HRPO approval for NICoE site, complete data collection on 25 concussed military participants
- Major Task 5: Once Tasks 1-4 are completed, analysis and optimization can be completed

4. **IMPACT:** Describe distinctive contributions, major accomplishments, innovations, successes, or any change in practice or behavior that has come about as a result of the project relative to:

What was the impact on the development of the principal discipline(s) of the project?
If there is nothing significant to report during this reporting period, state "Nothing to Report."

Describe how findings, results, techniques that were developed or extended, or other products from the project made an impact or are likely to make an impact on the base of knowledge, theory, and research in the principal disciplinary field(s) of the project. Summarize using language that an intelligent lay audience can understand (Scientific American style).

The findings/results/techniques from this project are still in the data collection phase, so we cannot state how they have made an impact yet. However, we can speculate as to their potential impact. The goal of this project is to provide a portable, objective assessment of balance using an Android-based smartphone app that can assist in the screening after a suspected mTBI. Our initial data showed that our app could pick up on balance dysfunction after low-level blast exposure in a military population, findings that we recently published in the peer-reviewed journal *Military Medicine*. While promising, that data was not optimal, so we recently developed Version 2 of the app, which have been used in all data collections moving forward. If successful, our app could have a large impact on the principle discipline (concussion detection) by providing an easy to use and cost effective means to measure balance dysfunction.

What was the impact on other disciplines?
If there is nothing significant to report during this reporting period, state "Nothing to Report."

Describe how the findings, results, or techniques that were developed or improved, or other products from the project made an impact or are likely to make an impact on other disciplines.

In addition to helping the military with concussion detection, it is plausible that our app could be used in other settings, such as sport-related concussion detection (i.e., sideline testing) or detection of balance dysfunction in a roadside test of a person suspected of driving under the influence.

What was the impact on technology transfer?
If there is nothing significant to report during this reporting period, state "Nothing to Report."

Describe ways in which the project made an impact, or is likely to make an impact, on commercial technology or public use, including:
- *transfer of results to entities in government or industry;*
- *instances where the research has led to the initiation of a start-up company; or*
- *adoption of new practices.*

Nothing to report

What was the impact on society beyond science and technology?
If there is nothing significant to report during this reporting period, state "Nothing to Report."

Describe how results from the project made an impact, or are likely to make an impact, beyond the bounds of science, engineering, and the academic world on areas such as:
- *improving public knowledge, attitudes, skills, and abilities;*
- *changing behavior, practices, decision making, policies (including regulatory policies), or social actions; or*
- *improving social, economic, civic, or environmental conditions.*

Nothing to report

5. **CHANGES/PROBLEMS:** The Project Director/Principal Investigator (PD/PI) is reminded that the recipient organization is required to obtain prior written approval from the awarding agency Grants Officer whenever there are significant changes in the project or its direction. If not previously reported in writing, provide the following additional information or state, "Nothing to Report," if applicable:

Changes in approach and reasons for change
Describe any changes in approach during the reporting period and reasons for these changes. Remember that significant changes in objectives and scope require prior approval of the agency.

- AccWalker/TARGET protocol:
  - CHANGE: improved the interface of the app
    - REASON: allows app to iterate through the tests based on the conditions and amount you would like to run at the time, generally makes it more user friendly

Actual or anticipated problems or delays and actions or plans to resolve them
Describe problems or delays encountered during the reporting period and actions or plans to resolve them.

- As stated previously, the FDA issue at UNCG delayed collection and recruitment for a month and a half

Changes that had a significant impact on expenditures
Describe changes during the reporting period that may have had a significant impact on expenditures, for example, delays in hiring staff or favorable developments that enable meeting objectives at less cost than anticipated.

- Nothing to report

Significant changes in use or care of human subjects, vertebrate animals, biohazards, and/or select agents

Describe significant deviations, unexpected outcomes, or changes in approved protocols for the use or care of human subjects, vertebrate animals, biohazards, and/or select agents during the reporting period. If required, were these changes approved by the applicable institution committee (or equivalent) and reported to the agency? Also specify the applicable Institutional Review Board/Institutional Animal Care and Use Committee approval dates.

Significant changes in use or care of human subjects

- IRB and HRPO approval:
  - UNCG/Temple:
    - Renewal: 9/14/2016
    - Modifications: 5/4/2016 (added filming component to BESS to reduce subjectivity in scoring) 8/30/2016 (added filming component to CB&M to reduce subjectivity in scoring), 9/26/2016 (updated recruitment flyer), 3/29/2017 (made FDA changes, increased inclusion criteria, expanded recruitment areas)

6. **PRODUCTS:** List any products resulting from the project during the reporting period. If there is nothing to report under a particular item, state "Nothing to Report."

- **Publications, conference papers, and presentations**
  Report only the major publication(s) resulting from the work under this award.

  Journal publications. *List peer-reviewed articles or papers appearing in scientific, technical, or professional journals. Identify for each publication: Author(s); title; journal; volume: year; page numbers; status of publication (published; accepted, awaiting publication; submitted, under review; other); acknowledgement of federal support (yes/no).*

Rhea, C.K., Kuznetsov, N.A., Ross, S.E., Long, B., Jakiela, J.T., Bailie, J.M., Yanagi, M.A., Haran, F.J., Wright, W.G., Robins, R.K., Sargent, P.D., & Duckworth, J.L. (2017). "Development of a portable tool for screening neuromotor sequelae from repetitive low-level blast exposure." *Military Medicine*, 182(3/4), 147-154 (accepted; federal support acknowledged)

Kuznetsov, N.A., Robins, R.K., Long, B., Jakiela, J.T., Haran, F.J., Ross, S.E., Wright, G.W., & Rhea, C.K. Validity and reliability of a portable tool for mTBI screening in military populations. (in preparation)

  Books or other non-periodical, one-time publications. *Report any book, monograph, dissertation, abstract, or the like published as or in a separate publication, rather than a periodical or series. Include any significant publication in the proceedings of a one-time conference or in the report of a one-time study, commission, or the like. Identify for each one-time publication: Author(s); title; editor; title of collection, if applicable; bibliographic information; year; type of publication (e.g., book, thesis or dissertation); status of publication (published; accepted, awaiting publication; submitted, under review; other); acknowledgement of federal support (yes/no).*

Nothing to Report

Other publications, conference papers, and presentations. *Identify any other publications, conference papers and/or presentations not reported above. Specify the status of the publication as noted above. List presentations made during the last year (international, national, local societies, military meetings, etc.). Use an asterisk (*) if presentation produced a manuscript.*

- Rhea, C.K., Kuznetsov, N.A., Robins, R.K., Jakiela, J.T., Long, B., Ross, S.E., Wright, W.G., Haran, F.J., Bailie, J.M., Yanagi, M.A., & Duckworth, J.L. Acute, sub-acute, and chronic effects on neuromotor performance after repeated low-level blast exposure. *Military Health System Research Symposium*, Kissimmee, FL, August, 2017, national conference, under review.

- Rhea, C.K., Kuznetsov, N.A., Robins, R.K., Jakiela, J.T., LoJacono, C.T., Ross, S.E., MacPherson, R.P., Long, B., Haran, F.J., & Wright, W.G. Dynamic balance decrements last longer than 10 days following a concussion. *International Society of Posture & Gait Research*, Ft. Lauderdale, FL, June 2017, international conference, podium.

- Kuznetsov, N.A., Robins, R.K., Jakiela, J.T., LoJacono, C.T., Ross, S.E., MacPherson, R.P., Long, B., Haran, F.J., Wright, W.G, & Rhea, C.K. Convergent validity of metrics provided by a portable gait assessment protocol. *North American Society for the Psychology of Sport and Physical Activity*, San Diego, CA, June 2017, national conference, under review.

- Kuznetsov, N.A., Jakiela, J.T., Ross, S.E., & Rhea, C.K. Adaptive fractal analysis of the center-of-pressure during the sensory organization test in individuals with concussion. *Human Movement Science & Biomechanics Research Symposium,* Chapel Hill, NC, March, 2017, regional conference, podium.

- Kuznetsov, N.A., Robins, R.K., Ross, S.E., Wright, W.G., Haran, F.J., Jakiela, J.T., Bailie, J.M., Yanagi, M.A., Long, B., Duckworth, J.L., & Rhea, C.K. Neuromotor testing post-mTBI: Reliability of movement metrics from a smartphone application. *Military Health System Research Symposium*, Kissimmee, FL, August, 2016, national conference, poster.

- Rhea, C.K., Kuznetsov, N.A., Bailie, J.M., Yanagi, M.A., Long, B., Haran, F.J., Ross, S.E., Wright, W.G., Robins, R.K., Jakiela, J.T., Sargent, P.D., & Duckworth, J.L. Concussion history influences neuromotor performance after exposure to repetitive low-level blast exposure. *American Society of Biomechanics*, Raleigh, NC, August 2016, national conference, poster.

- Rhea, C.K., Kuznetsov, N.A., Long, B., MacPherson, R.P., Jakiela, J.T., Robins, R.K., Haran, F.J., Ross, S.E., & Wright, W.G. Can a smartphone app be used to objectively measure neuromotor control after a concussion? *North American Society for the Psychology of Sport and Physical Activity*, Montreal, Quebec, June 2016, national conference, podium.

- Kuznetsov, N. A., Cone, B., Schleich, K.N., Hege, M.A., Ross, S.E., Long, B., Robins, R.K., Wright, W.G., Haran, F.J. & Rhea, C.K. Reliability of movement timing metrics provided by a portable gait assessment protocol. *North American Society for the Psychology of Sport and Physical Activity*, Montreal, Quebec, June 2016, national conference, podium.

- **Website(s) or other Internet site(s)**
  List the URL for any Internet site(s) that disseminates the results of the research activities. A short description of each site should be provided. It is not necessary to include the publications already specified above in this section.

Nothing to report

- **Technologies or techniques**
  Identify technologies or techniques that resulted from the research activities. In addition to a description of the technologies or techniques, describe how they will be shared.

Nothing to report

- **Inventions, patent applications, and/or licenses**
  Identify inventions, patent applications with date, and/or licenses that have resulted from the research. State whether an application is provisional or non-provisional and indicate the application number. Submission of this information as part of an interim research performance progress report is not a substitute for any other invention reporting required under the terms and conditions of an award.

Nothing to report

- **Other Products**
  Identify any other reportable outcomes that were developed under this project. Reportable outcomes are defined as a research result that is or relates to a product, scientific advance, or research tool that makes a meaningful contribution toward the understanding, prevention, diagnosis, prognosis, treatment, and/or rehabilitation of a disease, injury or condition, or to improve the quality of life. Examples include:
  - *data or databases;*
  - *biospecimen collections;*
  - *audio or video products;*
  - *software;*
  - *models;*
  - *educational aids or curricula;*
  - *instruments or equipment;*
  - *research material (e.g., Germplasm; cell lines, DNA probes, animal models);*
  - *clinical interventions;*
  - *new business creation; and*
  - *other.*

Nothing to report

7. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

What individuals have worked on the project?
Provide the following information for: (1) PDs/PIs; and (2) each person who has worked at least one person month per year on the project during the reporting period, regardless of the source of compensation (a person month equals approximately 160 hours of effort). If information is unchanged from a previous submission, provide the name only and indicate "no change."

> *Example:*
>
> | | |
> |---|---|
> | *Name:* | *Mary Smith* |
> | *Project Role:* | *Graduate Student* |
> | *Researcher Identifier (e.g. ORCID ID):* | *1234567* |
> | *Nearest person month worked:* | *5* |
> | | |
> | *Contribution to Project:* | *Ms. Smith has performed work in the area of combined error-control and constrained coding.* |
> | *Funding Support:* | *The Ford Foundation (Complete only if the funding support is provided from other than this award).* |

Name:	Christopher Rhea (UNCG)
Project Role:	PI
Researcher Identifier (e.g. ORCID ID):	n/a
Nearest person month worked:	7
Contribution to Project:	Lead of the study, developed protocol and analyses, oversees data collection/processing/analysis
Name:	Scott Ross (UNCG)
Project Role:	Co-Investigator
Researcher Identifier (e.g. ORCID ID):	n/a
Nearest person month worked:	4
Contribution to Project:	Oversees data collection/processing/analysis, responsible for assessment training (BESS)
Name:	Nikita Kuznetsov (UNCG)
Project Role:	Post Doc
Researcher Identifier (e.g. ORCID ID):	n/a
Nearest person month worked:	21
Contribution to Project:	Primary data collector/analyst, conducted reliability and validity studies on versions 1 and 2 of AccWalker, assisted in protocol modification
Name:	Jason Jakiela (UNCG)
Project Role:	Project Coordinator
Researcher Identifier (e.g. ORCID ID):	n/a
Nearest person month worked:	21
Contribution to Project:	Oversees the day to day of the study, prepares study documentation, assists in protocol modification and data collection/analysis

Name:	Ben Long (UNCG)
Project Role:	AccWalker Developer/Consultant
Researcher Identifier (e.g. ORCID ID):	n/a
Nearest person month worked:	4
Contribution to Project:	Application development and updating
Name:	Geoff Wright
Project Role:	Co-Investigator (Temple)
Researcher Identifier (e.g. ORCID ID):	n/a
Nearest person month worked:	6
Contribution to Project:	Leads study from Temple site, developed protocol and analyses, oversees data collection/processing/analysis
Name:	Becca Robins
Project Role:	Post Doc (Temple)
Researcher Identifier (e.g. ORCID ID):	n/a
Nearest person month worked:	19
Contribution to Project:	Primary data collector/analyst for Temple site, contributed to reliability/validity collection and analysis of AccWalker

Has there been a change in the active other support of the PD/PI(s) or senior/key personnel since the last reporting period?
If there is nothing significant to report during this reporting period, state "Nothing to Report."

If the active support has changed for the PD/PI(s) or senior/key personnel, then describe what the change has been. Changes may occur, for example, if a previously active grant has closed and/or if a previously pending grant is now active. Annotate this information so it is clear what has changed from the previous submission. Submission of other support information is not necessary for pending changes or for changes in the level of effort for active support reported previously. The awarding agency may require prior written approval if a change in active other support significantly impacts the effort on the project that is the subject of the project report.

Nothing to report

What other organizations were involved as partners?
If there is nothing significant to report during this reporting period, state "Nothing to Report."

Describe partner organizations – academic institutions, other nonprofits, industrial or commercial firms, state or local governments, schools or school systems, or other organizations (foreign or domestic) – that were involved with the project. Partner organizations may have provided financial or in-kind support, supplied facilities or equipment, collaborated in the research, exchanged personnel, or otherwise contributed.
Provide the following information for each partnership:
Organization Name:
Location of Organization: (if foreign location list country)
Partner's contribution to the project (identify one or more)
- *Financial support;*
- *In-kind support (e.g., partner makes software, computers, equipment, etc., available to project staff);*
- *Facilities (e.g., project staff use the partner's facilities for project activities);*
- *Collaboration (e.g., partner's staff work with project staff on the project);*
- *Personnel exchanges (e.g., project staff and/or partner's staff use each other's facilities, work at each other's site); and*
- *Other.*

- Organization: Temple University
  - Location: Philadelphia, PA
  - Contributions: collaboration
    - Data collection is concurrent with the Temple site for the civilian populations
- Organization: NICoE
  - Location: Bethesda, MD
  - Contributions: collaboration
    - Data collection for the military populations will be conducted at this site
- Organization: Uniformed Services University of the Health Sciences
  - Location: Bethesda, MD
  - Contributions: collaboration
    - Collected AccWalker data outlined in Major Task 3 were obtained from CDR Josh Duckworth via a DARPA funded project at the Uniformed Services University of the Health Sciences

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8. SPECIAL REPORTING REQUIREMENTS

COLLABORATIVE AWARDS: For collaborative awards, independent reports are required from BOTH the Initiating PI and the Collaborating/Partnering PI. A duplicative report is acceptable; however, tasks shall be clearly marked with the responsible PI and research site. A report shall be submitted to **https://ers.amedd.army.mil** for each unique award.

QUAD CHARTS: If applicable, the Quad Chart (available on https://www.usamraa.army.mil) should be updated and submitted with attachments.

TBI Assessment of Readiness using a Gait Evaluation Test (TARGET)

Log Number: MR130289
Award Number: W81XWH-15-1-0094

PI: Christopher K. Rhea, PhD   **Org:** University of North Carolina at Greensboro   **Award Amount:** $941,639

Study/Product Aim(s)

To determine the clinical utility of the TARGET for identifying motor impairment following mild traumatic brain injury (mTBI).

Approach

This award focuses on the development an mTBI screening test using an Android-device app for the assessment of motor impairment that will be (1) cost-effective, (2) deployable to a field-based setting, and (3) provide easily interpretable feedback (red light / green light) about a patient's neuromotor status. The TARGET protocol uses a smartphone app that detects movement patterns within a 70 stepping-in-place task. Based on initial data analyzed with this award, we have recently revised the app (Version 2) to include extra sensor information to increase our reliability and validity. Year 2 of this award will be dedicated to collecting civilians with and without mTBI, as well as military personnel in the chronic phase of mTBI so that the clinical utility of the TARGET can be determined.

RED LIGHT (impaired)
OR
GREEN LIGHT (normal functioning)

- The TARGET uses an Android app (top left) to collect movement patterns (top right)
- Unique algorithms are used to analyze the movement patterns to screen for mTBI

Timeline and Cost

Activities	Year 1	Year 2
Pre-Task: IRB/HRPO approval		
Major Task 1: healthy civilian		
Major Task 2: mTBI civilian		
Major Task 3: healthy military		
Major Task 4: mTBI military		
Estimated Budget ($941,639)	**$492,769**	**$448,870**

Updated: May 1, 2017

Goals/Milestones

Year 1 Goals
1. Obtain IRB approval & HRPO approval (Pre-Task)
   - ☑ UNCG IRB approval
   - ☑ Temple University IRB approval
   - ☑ HRPO approval at both sites
2. Collect civilian data (Major Tasks 1 & 2)
   - ☑ Recruit and test healthy civilians
   - ☐ Recruit and test civilians with mTBI

Year 2 Goals
3. Collect military personnel data (Major Tasks 3 & 4)
   - ☑ Recruit and test healthy military personnel
   - ☐ Recruit and test military personnel with mTBI

Comments/Challenges/Issues/Concerns
- Recruitment of mTBI civilians has been a challenge.
- To this end, we have reached out to more clinical partners and local universities to help expand our mTBI civilian reach.

Budget Expenditure to Date
Projected Expenditure: $941,639.00
Actual Expenditure: $738,905.03

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9. **APPENDICES:** Attach all appendices that contain information that supplements, clarifies or supports the text. Examples include original copies of journal articles, reprints of manuscripts and abstracts, a curriculum vitae, patent applications, study questionnaires, and surveys, etc.

Appendix A

Rhea, C.K., Kuznetsov, N.A., Ross, S.E., Long, B., Jakiela, J.T., Bailie, J.M., Yanagi, M.A., Haran, F.J., Wright, W.G., Robins, R.K., Sargent, P.D., & Duckworth, J.L. (2017). "Development of a portable tool for screening neuromotor sequelae from repetitive low-level blast exposure." *Military Medicine*, 182(3/4), 147-154

Development of a Portable Tool for Screening Neuromotor Sequelae From Repetitive Low-Level Blast Exposure

Christopher K. Rhea, PhD; Nikita A. Kuznetsov, PhD*; Scott E. Ross, PhD, LAT, ATC, FNATA*;
Benjamin Long, MS*; Jason T. Jakiela, MS*; Jason M. Bailie, PhD†‡; Matthew A. Yanagi, MS§;
LT F. Jay Haran, MSC, USN ‖; W. Geoffrey Wright, PhD¶; Rebecca K. Robins, PhD¶;
CDR Paul D. Sargent, MC USN**; CDR Joshua L. Duckworth, MC USN††*

ABSTRACT Blast exposure is a prevalent cause of mild traumatic brain injury (mTBI) in military personnel in combat. However, it is more common for a service member to be exposed to a low-level blast (LLB) that does not result in a clinically diagnosable mTBI. Recent research suggests that repetitive LLB exposure can result in symptomology similar to symptoms observed after mTBI. This manuscript reports on the use of an Android-based smartphone application (AccWalker app) to capture changes in neuromotor functioning after blast exposure. Active duty U.S. Navy personnel ($N = 59$) performed a stepping-in-place task before repetitive LLB exposure (heavy weapons training), and again immediately after, 24 hours after, and 72 to 96 hours after the completion of the training. The AccWalker app revealed that there are changes in neuromotor functioning after LLB exposure (slower self-selected movement pace and increased stride time variability) in participants who experienced neurocognitive decline. These data suggest that neurocognitive and neuromotor decline can occur after repeated LLB exposure.

INTRODUCTION

Traumatic brain injury (TBI) has received considerable attention within the military, as the number of injuries sustained has increased during Operations Iraqi Freedom and Enduring Freedom.[1] The majority of research on TBI has focused on mild traumatic brain injury (mTBI), synonymous with concussion, to severe TBI.[2] Two primary goals within the military mTBI literature are to provide information to enhance a clinician's ability to 1) identify functional deficits to aid in the clinical diagnosis of a mTBI and 2) make return-to-duty decisions. Much has been learned in this area and military specific guidelines have been developed to provide guidance and recommendations to clinical personnel in regard to mTBI screening, diagnosis, and injury management.[3,4] These guidelines require mandatory neurological and functional evaluations, which focus on changes sequela following a clinically diagnosed mTBI, including subjective symptomology, neurocognitive functioning, and neuromotor functioning (i.e., assessment of gait and/or balance).[5–7]

The aforementioned guidelines focus on the identification of mTBI following a head trauma event and very little is known regarding the effects of subclinical head perturbations. For example, do repetitive subclinical head perturbations result in cumulative functional deficits over time similar to those observed in a diagnosable mTBI?[8] The majority of subclinical head perturbations experienced by military members are a result of mechanisms similar to those seen in the sport domain (i.e., blunt-force trauma). However, a significant number of military personnel are exposed to subclinical head perturbations as a result of blast exposure associated with training. Blast exposure presents a potential risk for periventricular injury, rather than the diffuse axonal injury from direct impacts that result from blunt-force trauma, and which can cause a different neural cascade and may potentially result in a different presentation of sequelae.[9–11] Further, recent research has shown that blast exposure can lead to scarring across multiple interfaces in the brain, including the subpial glial plate, penetrating cortical blood vessels, gray-white matter junctions, and in the structures lining the ventricles.[12]

It is more than feasible that the aforementioned injury mechanisms can also result in subclinical head perturbations that do not lead to a diagnosable mTBI. What is currently unclear due to limited research, is whether the effects of repetitive blast exposure, especially low-level blast (LLB) exposure, experienced by military members during their training and operational careers has a cumulative effect similar to those associated with repeated subclinical head

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†Defense and Veterans Brain Injury Center, 1335 East-West Highway #600, Silver Spring, MD 20910.

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§SPAWAR Systems Center Pacific, 53560 Hull Street, San Diego, CA 92152.

‖Naval Submarine Medical Research Laboratory, Naval Submarine Base New London, Box #900, Groton, CT 06349.

¶Temple University, 1801 North Broad Street, Philadelphia, PA 19122.

**Naval Special Warfare Group ONE, 2000 Trident Way, San Diego, CA 92155.

††Uniformed Services University of the Health Sciences, 4301 Jones Bridge Road, Bethesda, MD 20814.

impacts in the sports domain.[13–19] It has been suggested that even mild brain perturbations can impair performance, and the potential sequelae of repetitive exposures require further attention.[20] As such, personnel at military breaching training schools have been studied in recent years to examine if there are any cumulative effects of repetitive LLB. Breacher training environments present a unique opportunity for research, as the environment isolates overpressure exposure as the primary mechanism of subclinical insults to the brain because it is unlikely that blunt-force or penetrating injury will occur.

In the seminal studies on the effects of repetitive LLB in breachers, neurocognitive deficits and changes in functional neuroimaging during a memory task were reported in only the training staff personnel with a chronic exposure history (i.e., number of blasts).[21–23] Stone et al reported differences in neuroimaging between breacher training course instructors with 7 to 15 years of experience when compared with personnel attending the 2-week course.[21] Carr et al reported that breachers with chronic blast exposure history self-reported more mTBI-related symptoms.[22] The authors also reported more severe symptoms when compared to a nonbreacher cohort, and a history of shoulder-fired weapons was found to be the most reliable predictor of symptomology outside of blast exposure history.[22] The results of these studies suggest that chronic LLB exposure may result in changes in symptomology, neuroimaging outcomes, and neurocognitive functioning.

To date, only one study has focused on the effects of repetitive short-term LLB exposure using a within-subjects design. Tate et al reported that military personnel attending 2-week breaching training course had changes in symptomology, biomarker loading, as well as neurocognitive deficits following course completion compared to baseline measurements.[23] This result is considerably important, as most repetitive LLB exposures occur in operational environments. It is critical that military personnel who may have suffered any severity of brain injury are properly identified near the time of injury so they can receive appropriate care as early as possible, and so that critical return-to-duty decisions can be made with appropriate clinical guidance.[23] This highlights the need for an objective means to diagnose and triage blast-exposed personnel in a field-based setting to not only screen for a possible mTBI, but also to identify any subclinical effects of the blast.

Much attention and funding has been devoted to developing field-deployable neurocognitive assessment tools (i.e., Defense Automated Neurobehavioral Assessment).[24–27] However, the ability to measure neuromotor function in a similar manner is currently lacking. The latest concussion consensus statement urged for inclusion of a gait and balance assessment to aid in clinical decision-making about neuromotor function.[28] To meet this challenge, we developed the AccWalker app (an Android-based smartphone application) as an objective, portable, field-based, and cost-effective tool for screening neuromotor sequelae following an insult or perturbation to the brain (i.e., blunt-head trauma or LLB exposure). The

AccWalker app captures the acceleration profile of the lower extremity during a stepping-in-place task, which is used to derive several metrics of gait timing as an assessment of neuromotor function. A stepping-in-place task was selected as a dynamic balance activity that is a surrogate of gait.[29]

The purpose of this project was to examine changes in neurocognitive testing and neuromotor functioning of military personnel who have been exposed to multiple subclinical head perturbations as result of their participation in a military heavy weapons (i.e., shoulder-fired weapons) training course to better understand the effects of repetitive short-term LLB exposure. Since neurocognitive testing is a well-accepted method to identify performance decline after head perturbations, our primary question was whether neuromotor performance decline was also present in this population. This was examined by splitting the studied population into two groups (with and without neurocognitive decline) and then determining whether neuromotor decline was also present. The rationale behind this design is that head trauma can lead to neurocognitive and/or neuromotor decline, but it is presently unclear if a decline in one domain (i.e., neurocognitive) generally leads to a decline in another domain (i.e., neuromotor). The reason the literature is unclear is two-fold: 1) most studies only focus on assessment in one domain after head trauma and 2) studies that have examined both domains have primarily focused on populations with blunt-force trauma leading to a concussion, not populations with repeated subclinical head perturbations. If the latter group experiences changes in neuromotor performance along with neurocognitive decline, that is important knowledge to discern, as it suggests that physical performance may suffer in this population in addition to cognitive performance. That knowledge could also be useful for medical professionals to ensure they more fully understand the service member's performance deficits and engage them in an appropriate treatment plan. Thus, the goal for this article was to determine whether neuromotor performance declines are observed after neurocognitive decline has been identified, not if one assessment method is more useful than the other in screening for mTBI. The neurocognitive data were used to split the studied population into two groups and then the rest of this manuscript focuses on the neuromotor testing. Our hypothesis was that the neuromotor decline would be observed in participants who exhibited neurocognitive decline and vice versa.

METHODS

Participants

Active duty U.S. Navy personnel ($N = 90$) who participated in a 21-day Desert Warfare Training Program completed the informed consent process as approved by the Institutional Review Board at Naval Medical Center, San Diego. From the total sample, 60 were trainees newly exposed to the heavy weapons training (as described below), 16 were control subjects who participated in the program, but did not

take the heavy weapons training, and 14 were Range Safety Officers. Four control subjects and one trainee were excluded from the analysis because they were only measured at baseline and left the training afterward due to medical or family reasons. The neuromotor data were also missing for one control subject in the baseline testing (BSL) and 5 control subjects in the immediate post-training testing (see Design section for the description of the measurement points). For the purposes of this article, we focus on the performance of trainees only ($N = 59$) because the number of measurements from the control and Range Safety Officer subjects was too little to break down by neurocognitive status.

Trainees were recruited voluntarily by research staff not associated with the military training program or by ranking members of their service. The mean age was 26.3 ± 3.5 years and all subjects were men. The mean time in military service at the beginning of the program was 4.2 years (SD = 2.9). Fourteen subjects have been previously deployed with a median number of deployments of 2 (maximum 7). The majority of participants were Caucasian ($N = 55$), whereas other participants were American Indian/Alaska natives ($N = 2$) and Hispanic ($N = 2$). The level of education in the sample was split into the following categories: no degree ($N = 14$), high school diploma ($N = 1$), some college ($N = 10$), Associate's degree ($N = 4$), Bachelor's degree ($N = 28$), and Master's degree and higher ($N = 2$). A subset of the participants ($N = 28$) self-reported having had a concussion in the past. In the majority of cases (all but 1) the concussion occurred more than 6 months before the training. Median number of self-reported concussions was 2.

Design

The Desert Warfare Training Program (heavy weapons training) lasted 21 consecutive days. This training included repetitive LLB exposure as part of the rocket fire training, which consisted of repetitive firing from shoulder-mounted rocket launchers such as M2CG 94mm (Carl Gustaf), M72 LAW 66mm (Light Anti-Tank Weapon), and RPG (Rocket-Propelled Grenades) with varying munitions.

On the second day of training, before any blast exposures, participants completed BSL in a battery of neurocognitive tests that included Hopkins Verbal Learning Test-Revised, components of the Defense Automated Neurobehavioral Assessment (Simple Reaction Time, Procedural Reaction Time, Go/No-Go), Trail Making Tests Parts A and B (TMT A & B), King-Devick Test (KDT), and performed the neuromotor test (stepping-in-place task with the AccWalker app). Approximately 7 days later, participants took part in the shoulder-mounted rocket launcher training. During this training segment, participants were outfitted with pressure Blast Gauge sensors (BlackBox Biometrics, Inc., Rochester, New York) placed on the anterior and posterior of the helmet, on the shoulder, chest, and back. The median number of blasts was 4 (minimum = 2 and maximum = 9). The maximum peak of pressure that occurred during training was 5.5, 7.3, 5.9, 4.8, and 8.5 pounds per inch (PSI) for the anterior head, posterior head, shoulder, chest, and back, respectively. The sum total impulse of the blasts was calculated as the integral of the positive overpressure data from the sensors. The total impulse that occurred during training was 7.5, 19.4, 15.7, 7.8, and 15.6 PSI-ms for the anterior head, posterior head, shoulder, chest, and back, respectively. Within 30 minutes on the completion of their initial rocket launcher training day, participants were tested on the neurocognitive battery of tests and on the neuromotor (i.e., stepping-in-place) test again (POST-1).

Individuals were classified with *neurocognitive decline* following blast exposure if their performance on neurocognitive testing in POST-1 was indicative of a reliable and significant change based on a priori cut-off scores on four measures of neurocognitive function: Hopkins Verbal Learning Test (Total Recall and Delayed Recall)[30] and Trail Making Test Part A and Part B.[31] A reliable change index (RCI)[32,33] was calculated for each cognitive measure; scores below the lower limit of a 90% confidence interval were indicative of decline. Reliable change indices were derived by estimating measurement error surrounding test–retest difference scores. Specifically, the standard error of the difference (S_{diff}) was used to create a confidence interval for the baseline-retest difference score. The formula used for calculating S_{diff} employed the standard error of measurement (SEM) for baseline (SEM_1) and the associated retest (SEM_2): $S_{diff} = \sqrt{SEM_1^2 + SEM_2^2}$. SEM_1 and SEM_2 were based on published normative data on the psychometric reliability of each measure. Participants classified with neurocognitive decline (29 out of 59 participants) were additionally tested 24 hours post-training (POST-2). All participants were tested again at 72 to 96 hours post-training (POST-3) (Fig. 1). This window was used due to participant availability for POST-3 testing.

Since the assessments for this project detracted for the 21-day Desert Warfare Training Program in which the subjects were participating, it was decided that all subjects would be tested at before LLB exposure (baseline, BSL) and immediately after LLB exposure (POST-1). To not further detract from their training, only participants who showed neurocognitive decline at POST-1 were tested 24 hours later (POST-2) to see if they still had their declined neurocognitive performance. All participants were then recruited back for testing 72 to 96 hours later (POST-3) to provide a third time point of assessment for all participants to measure performance before and after LLB exposure, and a fourth time point for those who exhibited neurocognitive decline to determine whether their neurocognitive performance returned to baseline levels. The specific focus of this article was to assess the neuromotor performance trajectory before and after LLB exposure in participants with and without neurocognitive performance declines.
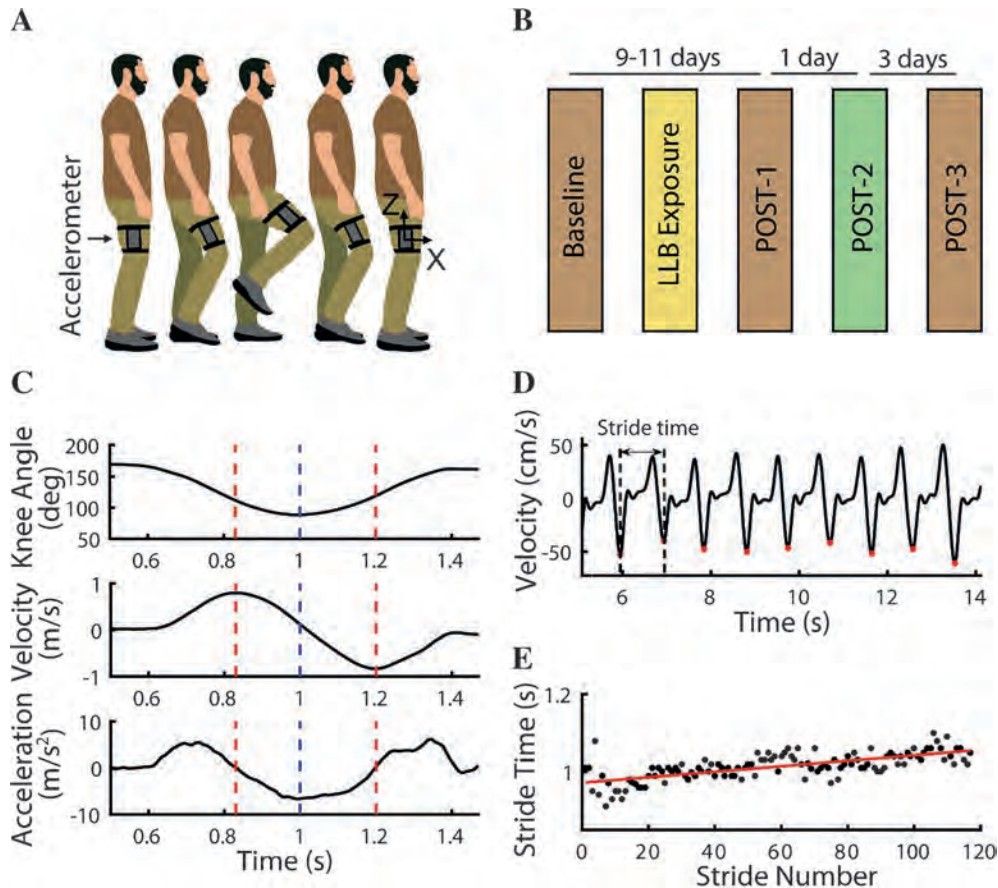
FIGURE 1. (A) Stepping-in-place task used for neuromotor testing. The las frame in the movement sequence shows the coordinate system of the phone with the AccWalker app in the sagittal plane. In the majority of trials, phone was placed on the thigh (as depicted in the figure). In a subset of trials (~12.6%), it was placed on the shank midway between the ankle and the knee, but this did not affect stride time estimation (see Methods section); (B) study design (POST-2 was only completed by participants with detected neurocognitive decline, $n =29$); (C) relation between the knee angle recorded via motion capture and thigh acceleration/velocity recorded by the AccWalker app; only phone acceleration was recorded by the phone in this study; (D) phone velocity on the leg was derived from recorded acceleration via integration (see Methods section). Stride time was defined based on velocity minima (peak velocity during leg return to stance); and (E) time series of the stride time as a function of step number within a single 120-second trial.

Materials

Six Android-based phones (Model GT-S7710L; Samsung Galaxy Xcover 2; Samsung, Seoul, South Korea) with the AccWalker app installed were used for the measurement of leg acceleration during the stepping-in-place task. The phone recorded acceleration along the x-, y-, and z-axes of the phone (Fig. 1A). The acceleration data were sampled at 96 Hz.

Procedures

During the neuromotor portion of testing, subjects were instructed to step-in-place at a comfortable walking pace for 120 seconds. The instruction was "Please walk in place" and the experimenter made sure they did not turn during the task and that they moved their arms in a symmetric fashion (Fig. 1A). The phone-based accelerometer was generally placed on the lateral side of the thigh, but in some cases (approximately 12.6% of total), size of the thigh did not permit proper placement of the strap and the accelerometer was placed on the shank. This difference in placement, however,

did not affect the calculation of movement timing variables during stepping in place because they both contained relevant timing landmarks (described below).

Dependent Measures

Preferred movement speed and variability of timing are commonly used to examine neuromotor ability in healthy and concussed individuals.[34–43] Accordingly, we examined stride time as a measure of neuromotor performance, which is defined as time between two equivalent landmarks during gait cycle of the same limb (i.e., heel strike, peak knee flexion, or any other identifiable landmark). We used the acceleration profile recorded by the AccWalker app to derive stride time mean, stride time SD, and its coefficient of variation (CV) to characterize timing performance during stepping-in-place. The CV (CV = SD/mean) was used because different individuals had different mean stride times in our sample, indicative of individual pacing preferences typically present for locomotor activities. CV provides a relative measure of

magnitude of variability that is independent from the mean stride time.

To obtain stride time measurements from the phone's accelerometer recordings, we used the following steps: 1) phone's acceleration along the z-axis of the phone was filtered with a fourth-order 5 Hz low-pass Butterworth filter, 2) filtered acceleration was integrated to obtain velocity, 3) velocity was high-pass filtered using a 0.25 Hz third-order polynomial adaptive filter[44] to remove the effects of accelerometer drift, and 4) stride time was identified based on timing between the consecutive minima in the velocity time series (Fig. 1D and E). Minimum velocity occurred when the leg was in midway of returning to the stance phase, between the maximum knee flexion and maximum knee extension (Fig. 1C). This landmark was used because it was robustly identifiable across different subjects and phone placements (thigh or shank). Using other landmarks (such as maximum velocity) did not alter the results. All computations were performed in Matlab 2015b (Mathworks, Natick, Massachusetts).

Statistical Analysis

We used a linear mixed model (LMM) to compare stride time measures as a function of testing time: BSL (baseline), POST-1 (immediately after weapons training), and POST-3 (72–96 hours post-training) and as a function of group assignment (neurocognitive decline vs. no-neurocognitive decline). POST-2 data were excluded from the LMM since only neurocognitive decline group data were collected. The p values for the main and the interaction effects were extracted by comparing the goodness of fit of the model with and without the effect of interest. A p value of <0.05 was considered as statistically significant. Post hoc tests were conducted using simple contrast comparisons using the Kenward–Roger approximation to the degrees of freedom. All analyses were conducted in R using lme4 and pbkrtest packages. The R code (The R Foundation, Vienna, Austria) for the full model

was: lmer(DV~Time*Group+(1|Subject),data,REML=0), where DV is the dependent measure, Time is factor specifying measurement time, and Group specifies neurocognitive status group. Subjects were specified as random effect. The covariance structure was set to be compound symmetric. The model was fit using maximum likelihood estimation.

We also calculated the statistical effect sizes for between- and within-groups across measured time points. The between-group effect size was defined using Cohen's d with the variance pooled across the two groups using root mean square. The within-group effect size was extracted by dividing the mean difference scores between the sessions by the SD of the difference scores.

RESULTS

Because of time constraints and other training environment factors, some participants missed some testing sessions. These observations were missing at random in the BSL (12 out of 59 missing, $N = 47$ tested), POST-1 (5 out of 59 missing, $N = 54$ tested), and POST-3 (10 out of 59 missing, $N = 49$ tested) sessions. Five observations showed substantial slowing down or speeding up of stride time during trial and these observations were removed from the analysis because drift affects the calculation of stride time-dependent measures, which require stationarity. See Figure 2 for the final number of measurements per group at each time point.

The results of the LMM analysis revealed a main effect of testing for mean stride time ($p < 0.001$). Post hoc t tests showed statistical differences between the BSL and POST-1, $t(131.46) = -6.35$, $p < 0.001$, $d = 0.73$, and the BSL and POST-3, $t(131.46) = -5.41$, $p < 0.001$, $d = 0.57$, indicating that mean stride time was greater at baseline than immediately after and 72 to 96 hours after LLB exposure. There was no main effect of neurocognitive status ($p > 0.05$) and no interaction effect ($p = 0.36$). However, the between-group effect sizes indicated that the difference between the
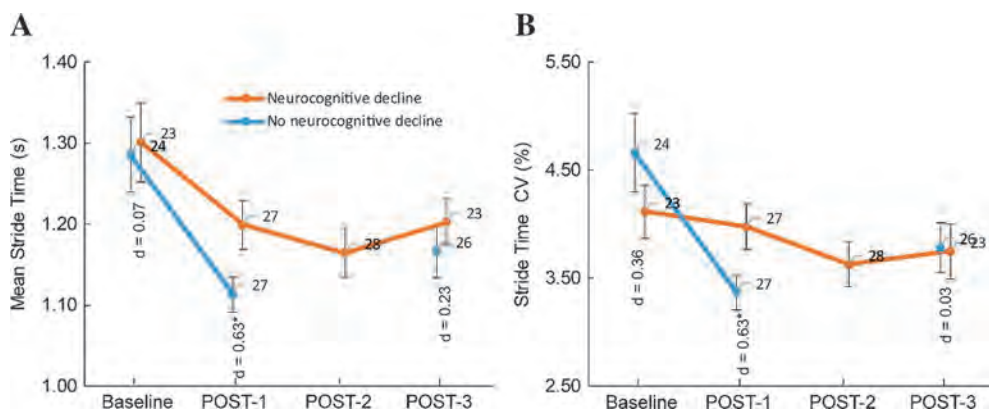

FIGURE 2. Changes in the movement timing parameters by group (neurocognitive decline vs. no-neurocognitive decline) as a function of blast exposure. Error bars depict standard error of the mean. Cohen's d is indicated for each between-group comparison with an asterisk denoting a statistically significant difference between the groups. Because of missing or unusable data, the n varies by time point and condition, which is represented by the number next to each data point.

neurocognitive decline and no-neurocognitive decline groups was greatest in the POST-1 condition (see Fig. 2A), suggesting that the group with the neurocognitive decline showed relatively slower stepping pattern than the group without neurocognitive decline.

The main effect of time for stride time CV was also significant ($p < 0.001$). There were statistical differences between the BSL and POST-1, $t(153.06) = -3.67$, $p < 0.001$, $d = 0.57$ and BSL and POST-3, $t(153.06) = -3.17$, $p = 0.001$, $d = 0.46$ (Fig. 2B). These results indicated that relative variability of movement timing was greater at baseline than immediately after and 72 to 96 hours after LLB exposure. There was also an interaction effect ($p = 0.014$) such that the difference between the groups was greater in POST-1 compared to baseline and POST-2, indicating that the neurocognitive decline group was more variable than the no-neurocognitive decline group. Between-group effect sizes across time points for the neurocognitive decline group vs. no-neurocognitive decline group are reported in Figure 2B.

DISCUSSION
The goal of article was to determine whether neuromotor performance declines are observed after neurocognitive decline has been identified after repeated LLB exposure. This goal was accomplished by developing a novel, objective, portable, field-based, and cost-effective tool to measure neuromotor function in a dynamic balance test in the context of military training environment. Our results showed that trainees with identified neurocognitive decline after LLB performed the stepping-in-place task slower and with a higher level of variability in stride time immediately after exposure to LLB compared to trainees without neurocognitive decline. Although both groups became faster and less variable on the stepping-in-place task as a function of repeated neuromotor testing, the relative divergence of performance immediately after LLB exposure suggests that neuromotor function can decline similarly with the neurocognitive performance after repeated subclinical head perturbations.

The overall increase of the stepping pace (lower mean stride time) and a decrease in stepping variability (lower stride time CV) from baseline to immediate testing sessions likely reflects a practice effect with this task in addition to any LLB effects. This interpretation is suggested by our recent follow-up work where we tested young healthy civilians not exposed to blasts or other potentially concussive events. In that civilian cohort, stride time CV decreased from the first to the second measurement to a similar extent (about 1%) as in the current dataset, where stride time CV was about 4.5% in the first test session to 3.5% in the second. Thus, practice effects should be accounted for in future research to more accurately determine the extent to which LLB alters neuromotor function. This could be done by mapping out the practice effect trajectory in the neuromotor task and including practice trials in future assessments of this test to negate the practice effect.

Even with the practice effect present, there was a clear divergence between groups in the mean stride time and stride time CV when they were tested immediately after range training (POST-1), suggesting repeated LLB exposure can lead to concurrent neurocognitive and neuromotor decline. It could be argued that the magnitude of change from baseline to POST-1 in the no-neurocognitive decline group reflects the practice effect from performing the stepping-in-place task a second time. Accordingly, a smaller change in movement pace and variability in the neurocognitive decline group could indicate less adaptive and slower practice effect in this task. As a result, subjects with identified neurocognitive decline were slightly slower (by about 100 milliseconds) and more variable in their performance than the no-neurocognitive decline group during testing immediately following range training (POST-1). Both slower pace of movement and increased movement variability are 2 typically observed gait alterations in individuals with TBI.[45,46] Collectively, our findings support previous research showing that cognitive ability predicts motor learning in patients with TBI.[47] It should be noted that the group differences in neuromotor performance dissipate by the POST-3 testing, suggesting that the effect of repeated LLB exposure on neuromotor control lasts less than 72 to 96 hours. However, the cumulative effect of chronic exposure to repeated LLB exposure remains an empirical question.

The finding that repeated LLB exposure is also associated with a decline in neuromotor performance is inconsistent with previous research showing that LLB exposure does not affect vestibular function.[48] However, repeated subclinical head perturbations have been shown to chronically affect neurological functioning in the sports domain,[13–19] so follow-up work with military personnel to track the effects of repetitive LLB exposure on acute and chronic neuromotor performance is warranted. Further, it should be noted that the blast level in this study was very low (5.5 and 7.3 PSI at the anterior and posterior of the head, respectively), which is only slightly above the recommended safety standard of 4 PSI.[22] Thus, blast magnitude and the number of blasts should be factored into to future studies to determine whether they lead to similar or divergent neurocognitive and neuromotor performance declines. The orientation of the head with respect to the LLB wave (i.e., consistently on the right or left side of the blast) may also influence the effect of LLB exposure neurocognitive and neuromotor performance.

There are a number of ways the neuromotor test described in this manuscript could be improved to increase its sensitivity to identify changes in neuromotor performance following subclinical head trauma. First, the level of difficulty in the stepping-in-place task could be increased to enhance the test's sensitivity. The task was completed with eyes open, so visual feedback about step timing and orientation in the environment was available. Performing the task with eyes closed would remove visual feedback, which has been shown to be a useful method in discriminating between participants with and

without head trauma.[49] Moreover, perturbing the vestibular system during the stepping-in-place task could also increase the sensitivity, as vestibular dysfunction affecting balance is common after head trauma.[50,51] Finally, previous research has suggested that gait velocity and medial–lateral range of motion of the trunk (or center of mass) during gait are strong indicators of neuromotor dysfunction after a concussion.[52–55] We measured leg movement timing, whereas trunk control, especially in the medial–lateral direction, may be affected in this subclinical population.

A number of limitations exist in this study. First, the most important limitation is that there is no control group that did not receive any LLB during training. We acknowledge that any change in neuromotor or neurocognitive performance could arise from a host of factors, including practice effects and other physical status changes (arousal, sleep deprivation, dehydration, etc.). There was limited data that could have been used a control group in this dataset, but it was not included in the results due to a low number of subjects in the session immediately following LLB ($n = 7$) and also because these subjects participated in training with different physical demands from the LLB-exposed trainees. Second, although some of the military personnel in our sample exhibited a significant decline in neurocognitive performance, a medical doctor was not present to evaluate any potential diagnosis of a concussion. Even though all of the blast waves were below known concussive thresholds, it is possible that some participants could have presented with concussion symptoms had they been examined by a medical doctor. Thus, we cannot definitively say that all participants experienced only subclinical perturbations.

In conclusion, we presented data from the first step in developing an objective, portable, field-based, and cost-effective tool to measure neuromotor function in a dynamic balance test. We showed that neuromotor decline accompanied neurocognitive decline in a subset of participants who were repeatedly exposed to LLB from heavy weapons training. This suggests that neurological dysfunction affects multiple domains of performance, which should be taken into account when deciding on appropriate medical care. It is especially important to note that all participants in this study were exposed to subconcussive LLB, adding to a growing body of research showing that repeated subclinical head trauma can affect neurological functioning.[13–19] Finally, although these early data are encouraging, the neuromotor assessment methods presented here are still in development and ultimately will require validation with medical outcomes data in order to have clinical utility.

ACKNOWLEDGMENTS

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Appendix B

Kuznetsov, N.A., Robins, R.K., Long, B., Jakiela, J.T., Haran, F.J., Ross, S.E., Wright, G.W., & Rhea, C.K. Validity and reliability of a portable tool for mTBI screening in military populations. (in preparation)

Validity and reliability of a smartphone app to quantify neuromotor function using a dynamic balance test

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Abbreviated title: Smartphone app to quantify dynamic balance

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Abstract

Postural control is frequently compromised after sub-concussive and concussive head trauma and balance testing is an integral part of neuromotor assessment and management. The main objective of this paper is to describe the development of a novel smartphone-based neuromotor assessment protocol for the screening of dynamic balance decrements stemming from head trauma in a field setting. Experiments 1 and 2 compared internal Android OS smartphone orientation detection algorithms to a biomechanics laboratory motion capture system using a pendulum (i.e., non-biological movement) and a human stepping (i.e., biological movement). Smartphone sensors provided valid measurements of movement timing and amplitude, as well as their variability. However, sensor firmware version and Android OS version significantly affected the quality of measurement. Experiment 3 established high test-retest reliability of a stepping-in-place protocol in three different sensory conditions (eyes open, no-vision, head shake) using temporal and kinematic variability metrics extracted from the thigh and trunk orientation signal in a sample of healthy young adults. Collectively, these experiments showed that our smartphone application is a valid and reliable way to measure dynamic balance, which could provide an objective way to assess neuromotor function after head trauma or in other populations where balance dysfunction may arise.

Key terms: smartphone sensors, assessment, gait, variability, reliability, validity, ICC

Introduction

Approximately 67-77% of individuals sustaining a mild traumatic brain injury (mTBI or concussion) report a sensation of dizziness and demonstrate transient postural instability[1] typically lasting about 3-10 days as measured using static balance tests such as Balance Error Scoring System (BESS) and Sensory Organization Test (SOT).[2] However, balance dysfunction persists longer in a smaller subset of individuals and resolves only with additional vestibular rehabilitation.[3] In line with these findings and in accordance with the most recent concussion management statement,[4] assessment of balance has become an integral part of comprehensive post-concussion symptom evaluation protocol.

Recent work in this domain has focused on the development of portable sensor-based balance assessment protocols that could be used by clinicians to screen for neuromotor symptoms of concussion in the field in order to make evidence-based return-to-play decisions and to track recovery of neuromotor function.[4] Rapid and objective screening is important because only a small number of concussive incidents are clearly identifiable based on visual observation (e.g., loss of consciousness) and a large number of sport concussions have subtle effects that are difficult to identify objectively.[5] Moreover, sub-concussive head trauma has received more attention in recent years.[6-10] This is due to the fact that sub-concussive head trauma is much more prevalent than concussive head trauma. For example, male collegiate football players receive approximately 1,000 head impacts throughout a season and only a very small number of them lead to a concussion, classifying the majority of head trauma as sub-concussive.[7] Both the short-term[11] and long-term[12] negative consequences of health-related behavior have been identified, justifying the need to better understand the role of sub-concussive head

trauma. Self-reporting of symptoms by athletes is one way to track the effects of sub-concussive or concussive head trauma and self-reporting has increased in the recent years, but a substantial number still remains unreported.[13] Thus, objective screening tools that can be implemented in the field would be beneficial to identify the effects of head trauma. To this end, there has been an increase in the number of sensor-based balance assessments availability to the research and clinical community, fueled by widespread access to portable technology such as smartphones and tablets, along with an improvement in the quality of sensors available in these devices.[14]

As an example of an instrumented portable balance test, SWAY Medical (Cleveland, OH) developed a comprehensive neurocognitive assessment that includes a static balance test with an iPhone (Apple Inc., CA) positioned around the thoracic region to record center of gravity fluctuations during quiet stance in different stance positions (e.g., feet together, single leg, and tandem stance).[15] BTracks (San Diego, CA) has developed a portable force plate[16] at a fraction of the cost of research-grade systems that allows to quantify center of pressure variability in the field setting.[17] Several research groups have also developed sensor-instrumented versions of the BESS.[18, 19]

One limitation of the current portable balance assessment protocols for head trauma evaluation is the over-reliance on testing of static postural control—maintenance of a fixed posture as still as possible in the absence of other movement. While static balance assessment is valuable, dynamic balance during activities such as walking or crossing over obstacles may be more sensitive to neuromotor symptoms of concussion[20, 21] and is more clinically relevant, as most sport-related concussive injuries happen during

dynamic activities. Thus, there is a need to develop head trauma screening tools that focus on dynamic balance activities.[22]

The second limitation of the current literature is that most sensor-based balance assessment protocols utilize accelerometers, frequently tracking center of mass dynamics based on lumbar region acceleration.[23] However, sensor tilt affects accelerometer values and sophisticated algorithms are required to remove these effectively. Utilizing smartphone sensors such as the gyroscope and magnetometer could provide better measurement quality and require less post-processing.

To address these limitations we developed a smartphone app and dynamic balance protocol to test neuromotor function using a dynamic balance test that consists of stepping-in-place in three sensory-probing conditions (eyes open, no-vision, and head shake). The rationale for these sensory manipulations was to emphasize proprioceptive and vestibular perturbations to the postural control system, as previous studies have indicated presence of visual and vestibular sensory processing deficits in individuals after a concussion.[24] This easy-to-complete task was selected because it allows for the collection of dynamic balance data using minimal space. The task is similar to the Fukuda test[25], except we do not focus on trunk rotation and positional displacement, as these variables have been shown to be invalid for the assessment of peripheral vestibular dysfunction.[26] Our focus is on characterizing temporal and kinematic variability of the leg and trunk movement during the dynamic balance task. This focus was selected because motor variability (both magnitude and structure) is commonly-used marker of neurological dysfunction.[27] To record dynamic balance variability, we developed a smartphone application (AccWalker) that quantifies thigh and trunk orientation using smartphone's

gyroscope, accelerometer, and magnetometer sensors. The aim of this paper is to describe the validation of AccWalker in comparison to laboratory motion capture equipment (Experiments 1 and 2) and to report test-retest reliability of the dynamic balance protocol in a sample of healthy young adults (Experiment 3).

Experiment 1: Android Orientation Sensor Validation

Experiment 1 evaluated AccWalker's performance to detect phone orientation in comparison to a research-grade motion capture system using simple and reproducible pendulum movement. Two different versions of Android Operating System (Android OS 4.4.4 and 5.1) were tested to check for differences in orientation estimation. We hypothesized that the AccWalker would produce valid pendulum angle measurement with respect to motion capture and that the two versions of Android OS would provide equivalent pendulum angle measurements.

Materials and Methods

A physical pendulum was constructed from a square poplar wood plank (L = 95 cm, m = 57 g) attached to a wheel bearing at the pivot point (Figure 1A). Motion capture markers (5 g) were placed on the pendulum's arm and the pivot point. The phone (Motorola Moto X2 XT1095, 144 g) was placed at the end of the pendulum arm. The pendulum was released from an angle of 30° and the resulting oscillation was recorded for 60 s. Motion capture data were used to calculate pendulum angle, θ, with respect to the vertical as:

$$\theta = \mathrm{acos}\left(\frac{\boldsymbol{A} \cdot \boldsymbol{B}}{\|\boldsymbol{A}\|\|\boldsymbol{B}\|}\right) \tag{1}$$

,where **A** is the vertical 2D vector starting at the pivot and pointing straight down and **B** is the vector pointing from the pivot to the marker on the pendulum's arm.

Phone orientation was estimated based on the gyroscope, accelerometer, and magnetometer sensors using the Rotation Vector function from Android SDK 4.4W.2 API 19.[28] Android sensor fusion involves integration of the gyroscope signal with drift-correction using accelerometer and magnetometer signals. Orientation of the device was first estimated using TYPE_ROTATION_VECTOR sensor, which captures 3D orientation of the phone using axis-angle representation with respect to the world coordinate system.[28] We then used getRotationMatrixFromVector function to obtain the rotation matrix and getOrientation function to obtain device's orientation in Euler angles based on the rotation matrix as described on the Android's sensor implementation webpage.[29] See Supplementary material for the code accomplishing these steps.

Resulting Euler angles characterize the sequence of rotations of the phone's local coordinate system (**xyz**)[30] with respect to the global coordinate system (**XYZ**), where **Y** is a unit vector tangential to the ground at the device's current location and pointing toward the magnetic north, **Z** points towards the center of the Earth and is perpendicular to the ground, and **X** is defined as the vector product of **Y** and **Z**, tangential to the ground at the device's current location and roughly points East. The order of Euler rotations was ZXY. The angle corresponding to the pendulum angle is the Euler rotation around the Z axis—this angle corresponds to the phone orientation with respect to the vector perpendicular to Earth's surface.

The AccWalker app was installed on Motorola X2 XT1095 (Schaumburg, IL) because it was relatively inexpensive and has good-quality sensors required by the

Rotation Vector function: a 3-axis accelerometer, a 3-axis gyroscope (InvenSense Inc., MPU-6515 MEMS, San Jose, CA), and a 3-axis magnetometer (Asahi Kasei Corp, AK8963, Tokyo, Japan).

The 3D motion capture system (Qualisys, Gothenburg, Sweden) data were sampled at 100 Hz, while the AccWalker data were sampled at approximately 100.86 Hz (SENSOR_DELAY_FASTEST setting) due to sampling asynchronies inherent to the Android sensor framework.[31] AccWalker recordings were interpolated and resampled at 100 Hz using cubic spline interp1.m in Matlab 2016b (Mathworks, Natick, MA). The signals were filtered using the 4th-order 5 Hz low-pass Butterworth filter and angular velocity was calculated using the 3-point formula. Motion capture and phone recordings were time-synchronized using a velocity spike resulting from a finger tap on the phone prior to trial onset.

Three trials of pendulum oscillation were recorded to compare the performance of the AccWalker app running on Android 4.4.4 and 3D motion capture. Stock KitKat 4.4.4 OS was downloaded from the XDA Developers forum and installed on the phone using TWRP software. Three additional trials were performed using the same phone after updating the OS and sensor framework to Android 5.1.

Results

Pendulum angle recorded by the motion capture and the AccWalker were visually similar (Figure 1B). The mean absolute difference between the maxima of the two recordings was 0.35º (SD = 0.14º). The average timing difference between the maxima was 0.009 s. Mean absolute difference was 1.0º (SD = 0.17º), and the timing difference was 0.01 s for the minima.

The AccWalker angular trajectory differed slightly from the motion capture in the initial 5-6 oscillations (Figure 1C), primarily due to an asymmetric velocity profile near peak velocities (Figure 1E). However, the AccWalker velocity became more symmetrical and similar to motion capture later in the recordings (Figure D) when the absolute maximum velocities were around 50 deg/s (Figure 1F). In addition, both signals were plotted in phase space to simultaneously visualize the angle and angular velocity of the pendulum illustrating this observation (Figure 1G and H).

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Insert Figure 1

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Performance of the AccWalker significantly degraded after upgrading to Android OS 5.1 (Figure 2). Upper panels of Figure 2 show AccWalker recordings of the pendulum oscillation (orange) and corresponding phase space (blue) when running Android 4.4.4, while the lower panels show the performance of the same phone after upgrading it to Android 5.1. The AccWalker showed substantial drift in the estimated pendulum angle after the OS upgrade.

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Insert Figure 2

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Discussion

The main finding of Experiment 1 is that the smartphone orientation sensor implemented in our smartphone app, AccWalker, provides an accurate measurement of pendulum angle kinematics in comparison to a research-grade motion capture when

running on Android OS 4.4.4, but not on Android 5.1. Information provided in this experiment is crucial to understand the limitations of internal Android functions for orientation estimation prior to using smartphones to accurately quantify human movement kinematics outside the lab.

When running Android OS 4.4.4, AccWalker angle measurements differed from motion capture by only 0.35º to 1.0º, which is consistent with previously reported values for inertial measurement units.[32] This result suggests that the sensor fusion algorithm implemented by InvenSense (San Jose, CA) on Motorola Moto X2 running on Android 4.4.4 is of sufficient quality for orientation measurement of human motion. The phone may have performed sub-optimally on Android 5.1 because the MPU-6515 sensor (the accelerometer and gyroscope unit) has internal fusion algorithms that were specifically optimized for inertial orientation tracking in smartphones running Android 4.4 as described in manufacturer's specifications.[33] The degree to which other smartphones would be susceptible to the same issues with OS upgrades needs to be tested for each phone independently prior to using them for human motion analysis applications. Similar issues were identified in different versions of iPad for the quantification of reaction time.[34]

Two other issues became apparent: First, the phone must be oriented parallel to the plane of motion to detect pendulum angle accurately (i.e., phone's screen should be perpendicular to the plane of pendulum oscillation). As we describe in Experiment 2, tilting the phone with respect to the dominant plane of motion reduces accuracy of angle amplitude estimation. Second, magnetic field sources affect orientation measurements and prevent the Rotation Vector function from initiating. In our experience, the Rotation Vector function stopped working when the strength of the field was greater than 130 μT.

The solution is to remove the source of magnetic field and re-calibrate the phone by performing figure-8 calibration.[35]

Our pendulum setup can be used in future studies to validate smartphone orientation detection algorithms. Phone manufacturers may switch sensor suppliers without clearly specifying these changes in the product description. Moreover, changing software versions, as we showed, can influence the data recorded by the sensors. It is impossible to know *a priori* how such changes in the components and/or software may affect the quality of orientation detection. In addition, the OS may automatically update during data collection for a study, significantly compromising data quality.

Experiment 2: Concurrent validity of AccWalker and 3D motion capture during stepping-in-place and treadmill walking

Experiment 2 tested the validity of AccWalker to measure temporal and kinematic variables of thigh and trunk motion during stepping-in-place. The stepping-in-place task was used to assess dynamic balance control, with the postulate that reduced neuromotor control would be amplified in temporal and kinematic variables in a dynamic balance test relative to a static balance test. We hypothesized that AccWalker and 3D motion capture would provide similar estimates of thigh and trunk motion during this task and we used the Bland-Altman limits of agreement test (LOA)[36] to test this hypothesis. In addition, we examined the ability of the phone to detect stride time variability during treadmill walking because temporal metrics are of primary interest for many neuromotor assessments. Lastly, since perfect orientation of the smartphone sensor during testing in the field may

not always occur, we evaluated the effects of slight anterior misplacement of the phone on the measurement of thigh orientation.

Materials and Methods

Participants

A convenience sample of 9 healthy young adults (mean age 25.12 ± 2.86 yrs; 8 men) took part in the study after signing a consent form approved by the Institutional Review Board (IRB) at the University of North Carolina at Greensboro.

Materials

Two identical smartphones (Motorola Moto X2; Android OS 4.4.4) were used to measure thigh and upper trunk orientation (Figure 3). The leg phone measured absolute thigh segment angle with respect to the vertical in the anterior-posterior (AP) plane. The trunk phone measured orientation of the upper trunk with respect to the vertical in the medial-lateral (ML) plane. The leg phone was secured using a phone strap (Belkin, Playa Vista, CA) and the trunk phone was secured using a chest mount (Velocity Clip, Richmond, CA). Phone orientation methods and data processing were the same as in Experiment 1.

Motion capture markers were placed on the skin over the greater trochanter, knee, lateral malleolus, L4, and T12 using adhesive tape. The absolute thigh segment angle was calculated using Equation 1, where **A** was a 2D vector in the sagittal plane starting at the greater trochanter marker and ending at a point straight down from the trochanter marker (this point was determined by offsetting the z-coordinate of the trochanter marker by 0.1 m) and **B** was a vector starting at the greater trochanter marker and ending at the knee marker. The ML trunk angle was defined as the angle between the 2D vector in the

coronal plane connecting L4 to T12 and the vertical vector staring at L4 and pointing up. Simultaneous recordings from the motion capture and phone were time-synchronized based on the first thigh flexion peak during the trial.

Procedures

Each participant performed two trials of stepping-in-place. The instruction was to synchronize each step to an auditory metronome (period = 1.15 s) for the first 10 seconds and then to continue stepping at the same pace for 60 s. Participants were asked to use comfortable range of motion at the hip and knee, to lift the foot fully off the ground, and to maintain visual fixation on the target located 1.5 m in front of them at the eye level. An additional stepping-in-place trial was performed with the phone shifted anteriorly on the thigh (~4-5 cm) (Figure 3C) to simulate the effects of improper phone placement on the calculation of temporal and kinematic variables of the leg movement described below. Participants were also recorded walking on a treadmill at 1.34 m/s.

Dependent measures

Temporal metrics. Stride time was identified based on maximal thigh flexion. Average stride time (expressed both as a percentage of the target period and as an absolute value) was used to characterize how well the participants maintained metronome pace throughout the trial. Stride time change throughout the trial (Pace drift) was quantified as the absolute difference of the average stride time during the first and last 5 s of the trial. Coefficient of variation (CV) and autocorrelation at lag 1 (ACF1) were used to characterize the magnitude and structure of stride time variability, respectively.

Kinematic metrics. Kinematic variability was characterized using the standard deviation of: 1) phone angle at the peak thigh flexion (Peak Thigh SD), 2) peak velocity

during leg lift (Lift Velocity SD), and 3) peak velocity during leg return (Return Velocity SD). Thigh range of motion (Thigh ROM) was quantified as the difference between the average phone angle during stance and the average phone angle at maximum thigh flexion. We also calculated the CV of the phone angle at maximal thigh flexion (Peak Thigh SD/Thigh ROM) to control for potential difference in signal-dependent noise due to different ranges of motion adopted by the subjects.

Trunk movement. Variability of trunk movement in the ML plane was quantified using standard deviation of the phone angle and velocity.

Statistical analysis

The standard deviation of LOA (SD LOA) and 95% LOA were estimated using a method for designs with replicates[37] and implemented in *R*[38] using the *BA.est* function from the *MethComp* library.[39] The criterion for validating the AccWalker against motion capture was based on the ratio of the SD LOA over the between-subject SD calculated from the motion capture recordings. If the expected deviation of the AccWalker metric from motion capture (SD LOA) was smaller than the true inter-individual differences (best estimated from the SD of 3D motion capture), then this metric was more likely to discriminate true individual differences in performance and would be useful for detection of performance decrements due to head trauma. The ratio ranges from 0% to 100% (and greater, if SD LOA is larger than the SD of motion capture). A ratio less than 100% indicates that the expected magnitude of variability between the measurement systems is smaller than the observed magnitude of individual differences.

Results

Stepping-in-place. Exemplary thigh angle and angular velocity time series are presented in Figure 3. The thigh angle and angular velocity measurements were in close correspondence between the systems when the phone was properly placed on the thigh (i.e., phone screen is perpendicular to the thigh motion in the AP plane; Figure 3A). Placing the phone more anteriorly decreased the amplitude of the thigh angle and velocity measurement by the AccWalker (Figure 3C), but did not affect peak thigh flexion timing. ML trunk velocity corresponded to 3D motion capture measurement more closely than the ML trunk angle (Figure 3D). The next section quantifies this qualitative description.

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Insert Figure 3

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Table 1 presents the LOA results for each variable. All AccWalker measures were valid with respect to motion capture because the SD LOA was always smaller than the individual differences detected by 3D motion capture (SD LOA/SD < 100%). For example, SD LOA for stride time CV was only 21.88% of the between-subject variability detected by the motion capture (0.07/0.32*100). Stride time CV was 2.06% when estimated from the motion capture recordings vs. 2.07% for the AccWalker, with bias of 0.01% and 95% LOA [-0.11 to 0.15]. Other metrics showed similar pattern of results, suggesting that the AccWalker is valid for the measurement of the temporal variables characterizing stepping-in-place.

AccWalker slightly overestimated thigh ROM (bias 2.65º), but the SD LOA for this measurement was only 15.95% of the expected inter-individual differences, indicating that

the measure is valid. Thigh ROM measurement by AccWalker was also was within reasonable clinical limits for error in angle detection [-0.15 to 5.37º]. Trunk angle and velocity measurements were more variable between the systems, but this variability was smaller than the inter-individual variability (88.78 and 76.44%, respectively), indicating that the trunk motion metrics produced by the AccWalker were valid.

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Insert Table 1

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Shifting the phone anteriorly on the thigh (Figure 3C) worsened AccWalker performance as indicated by increased SD LOA/SD ratios for both temporal and spatial metrics (Table 2). For example, the SD LOA/SD for stride time CV increased from 21.88% (when the phone was properly placed) to 45% and peak thigh SD increased from 14.04% to 36.82%. However, such increases were within reasonable limits because the discrepancy between the systems was still smaller than the magnitude of individual differences detected by the motion capture (SD LOA/SD < 100%). In addition, lack of appreciable changes in bias in any of the metrics suggests that the AccWalker was still providing valid measurements despite phone misplacement. Shifting the phone mostly affected thigh ROM, which was 11.47^0 smaller than the true ROM detected by the motion capture, making this measurement invalid. This also invalidated the normalized peak thigh flexion variability metric (Peak thigh SD/ROM).

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Insert Table 2

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Treadmill walking. AccWalker provided valid measurements of stride time and its CV, ACF1, and drift during treadmill wakling. The SD LOA/SD for stride time CV was 30.64% (see Supplementary Table I).

Discussion

The main result of Experiment 2 is that the AccWalker provides valid measurement of temporal and kinematic variables of thigh and trunk movement during the dynamic balance test. Specifically, mean stride time, stride time CV, autocorrelation, and drift in pacing were valid temporal metrics. All kinematic metrics of thigh motion were valid as well, with the variability in peak thigh velocity being the most variable between the AccWalker and motion capture. Placing the phone more anteriorly on the thigh to simulate the effects of improper placement degraded AccWalker's performance, but it was still within acceptable validity limits for all timing and most of the kinematic metrics—apart from introducing large bias to thigh ROM measurement. This result indicates that thigh ROM is invalid if the phone is not oriented within the dominant plane of motion, but the other identified metrics are acceptable. These results set the foundation for the use of these movement metrics in a dynamic balance test that has sensory probing conditions.

Experiment 3: Test-retest reliability study

Experiment 3 sought to evaluate the test-retest reliability of the valid AccWalker metrics in a sensory probing dynamic balance protocol consisting of the eyes open (EO), no-vision (NV), and head shake (HS) while stepping-in-place. We hypothesized that the stepping-in-place protocol would show minimal practice effects with high test-retest reliability within each condition.

Materials and Methods

Participants

32 healthy young adults (14 men and 18 women; mean age 24.66 ± 4.73 yrs) took part in the study. Participants were undergraduate and graduate students in the Department of Kinesiology at the University of North Carolina at Greensboro and the Department of Physical Therapy at Temple University. All participants signed a consent form prior to beginning the study with the procedures approved by the IRBs at both universities.

Procedures

Three different conditions of stepping-in-place (eyes open, no-vision, and head shake) were performed in the order listed, with three trials per condition (Figure 4A). The procedures and the instruction for the eyes open condition were the same as in Experiment 2. In the no-vision condition, participants wore a taped-over ski mask and did not remove it between trials. This ensured that participants were not aware of any change in their heading or position that occurred during the no-vision trials and did not attempt to deliberately correct for it in the subsequent trial. In the head shake condition, participants were instructed to laterally move their head side-to-side (about 20º) while mainintaining visual fixation on the target in front of them. They were instructed to couple their head movement to the leg movement and to keep moving their head continuously throughout the trial. Subjects performed two sessions of the protocol separated by approximately a week (7.31 ± 1.2 days on average).

Materials

Phone specifications and placement were identical to Experiment 2. Head yaw angle was measured using the XSens inertial measurement unit (MTw Development Kit, Enschede, Netherlands) during the head shake condition only.

Statistical analysis

Intra-class correlation coefficient ICC(2,k) was used to estimate test-retest reliability because this ICC type incorporates both systematic and random error.[40] Standard error of the mean was included as a measure of absolute reliability.[40] Three trials per condition were averaged and used for a one-way repeated-measures analysis of variance (ANOVA) with Session (1 vs. 2) as a within-subjects factor, performed separately for each experimental condition for calculating the ICC and SEM.[40, 41] ICC values were interpreted as follows: < 0.40 = poor, 0.40 – 0.59 = fair, 0.60 – 0.74 = good, ≥ 0.75 = excellent, and ≥ 0.70 = clinically acceptable.[42] Head range of motion and velocity in the horizontal plane were also evaluated for practice effects. The alpha level for the main effect of session was set at 0.1 to provide a more liberal estimate of practice effect presence as suggested in Fleiss.[42] We also examined the effect of sensory conditions using a Condition×Session repeated-measures ANOVA, followed up with post-hoc *t*-tests. The alpha value was set at 0.05 for these comparisons.

Results

The ICC(2,k) and SEM for all dependent measures are presented in Table III. Mean stride time, stride time CV, peak thigh flexion SD, thigh ROM, and thigh velocity maxima all showed excellent reliability (ICC > 0.75) in each of the sensory conditions. However, there were practice effects for stride time CV in the HS condition, for peak thigh

SD in the no-vision and head shake, and for trunk ML Velocity SD in the head shake condition as illustrated in Figure 4C.

Stride time CV was greater in the no-vision and head shake conditions compared to eye open condition (both p's < .01). The thigh ROM was lower in no-vision and head shake conditions compared to eyes open condition (p = .01 and p < .001, respectively). The Trunk ML Velocity SD was greater in the head shake condition compared to no-vision and eyes open conditions (both p's < .01).

The horizontal range of motion adopted by participants in the head shake condition was 62.69º (SD = 14.03º) and 61.18º (SD = 11.81º) in session 1 and 2, respectively, p = .23. Peak head velocity was 179.50 º/s (43.31) and 177.78 º/s (35.58) in session 1 and 2, p = .30, which is greater than the minimally required velocity to activate the vestibular-ocular reflex (85 deg/s). However, variability of peak head velocity decreased from session 1 (M = 22.43, SD = 5.97) to session 2 (19.82, SD = 4.66), p < 0.01.

Discussion

Results of Experiment 3 indicate that the AccWalker produces reliable test-retest measurements during a dynamic balance test. The reliability of stride time CV and kinematic variability metrics (peak thigh SD, thigh ROM, SD of thigh velocity) were clinically acceptable as indicated by ICC values greater than 0.70 in all sensory conditions of the stepping-in-place protocol. However, these metrics (except thigh ROM) are also subject to practice effects primarily in the no-vision and head shake conditions, with the second session being less variable. This information is useful to further prune the variables characterizing balance performance in this task and to fine-tune the stepping-in-place protocol in the eyes closed and head shake conditions.

Practice effects are problematic for head trauma screening because they add an additional factor affecting motor variability above and beyond any changes in the neuromotor status due to head trauma, making it difficult to interpret minimum detectable change scores from baseline. However, other balance tests such as the Neurocom Sensory Organization Test and the Balance Error Scoring System have been reported to have practice effects as well.[43, 44] One way to mitigate this is to provide more practice with the task, or even perform a pre-test before the pre-season assessment. At the same time, our dynamic balance task may be more taxing for individuals after head trauma than static balance testing and their performance may still show deterioration regardless of any practice effects. The next step would be to perform discriminant validity study to test the hypothesis that our dynamic balance protocol successfully detects variability alterations after head trauma. In our previous work using repeated neuromotor assessments with a similar smartphone app and dynamic balance protocol, we could successfully identify stride time CV changes after sub-concussive head trauma due to low-level blast exposure.[45]

Differences between the sensory conditions followed the expected pattern, as the visual and vestibular perturbations generally increased movement variability.[46] The reduction of the range of motion in the no-vision and head shake conditions is consistent with previous studies documenting decreased gait velocity while walking without visual input[47] and may be related to an attempt to reduce the risk of falling by lifting the foot less. Trunk velocity was highest in the head shake condition, which may be related to the increased trunk movement and to the destabilizing vestibular effect on the function of the horizontal semi-circular canals.

A limitation of current study is the short duration between the test-retest sessions. Also, we do not envision field-based researchers and clinicians using our smartphone app and dynamic balance protocol measuring head kinematics as was done in Experiment 3, which would make it more difficult to ensure that the vestibular-ocular reflex was activated. To address this, the person administering the test would need to inspect and rate visual fixation performance.

In conclusion, we have developed a reliable and valid assessment tool for dynamic balance testing and have created a reliable experimental task challenging the balance system. Our dynamic balance task and smartphone app would be useful to quantify dynamic balance in a variety of population with neurological dysfunction, such as populations such as chronic ankle instability, older adults, of populations with sub-concussive or concussive head trauma.
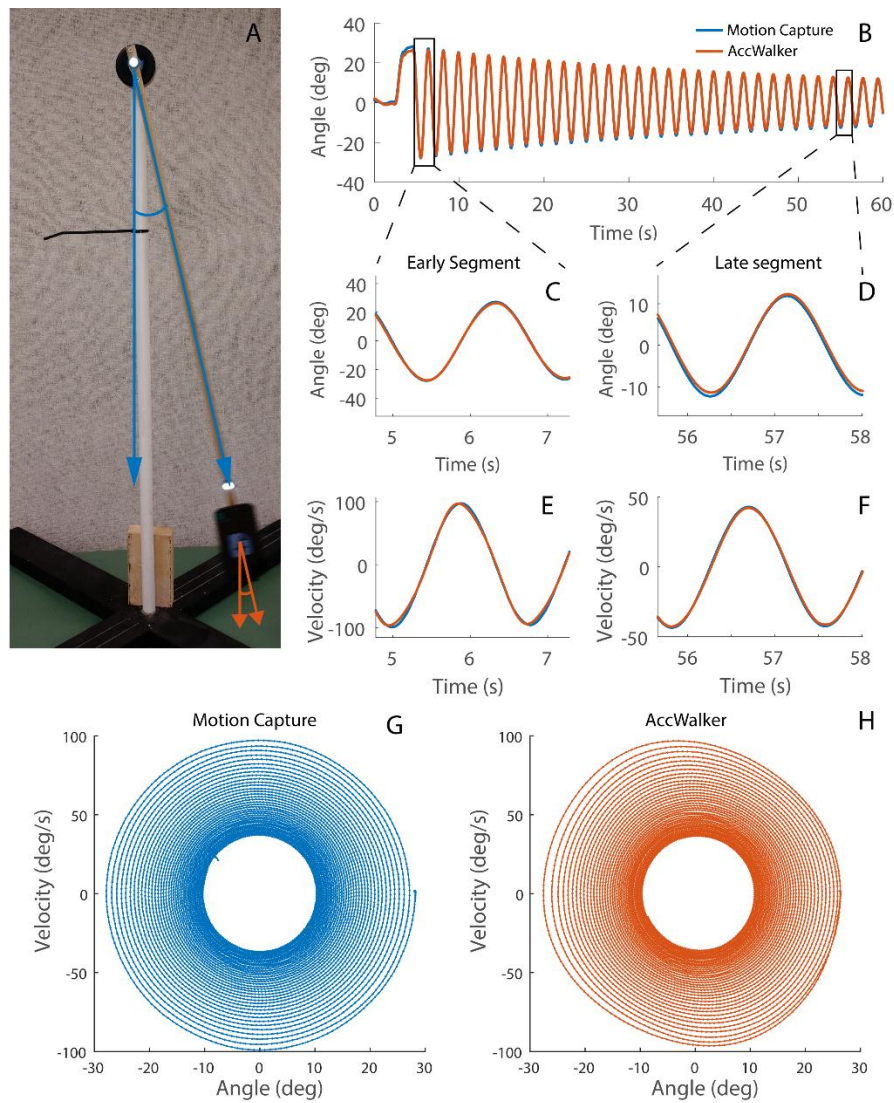
Acknowledgments

Figure 1. Testing of the AccWalker to detect pendulum angle in comparison to Qualisys motion capture system.
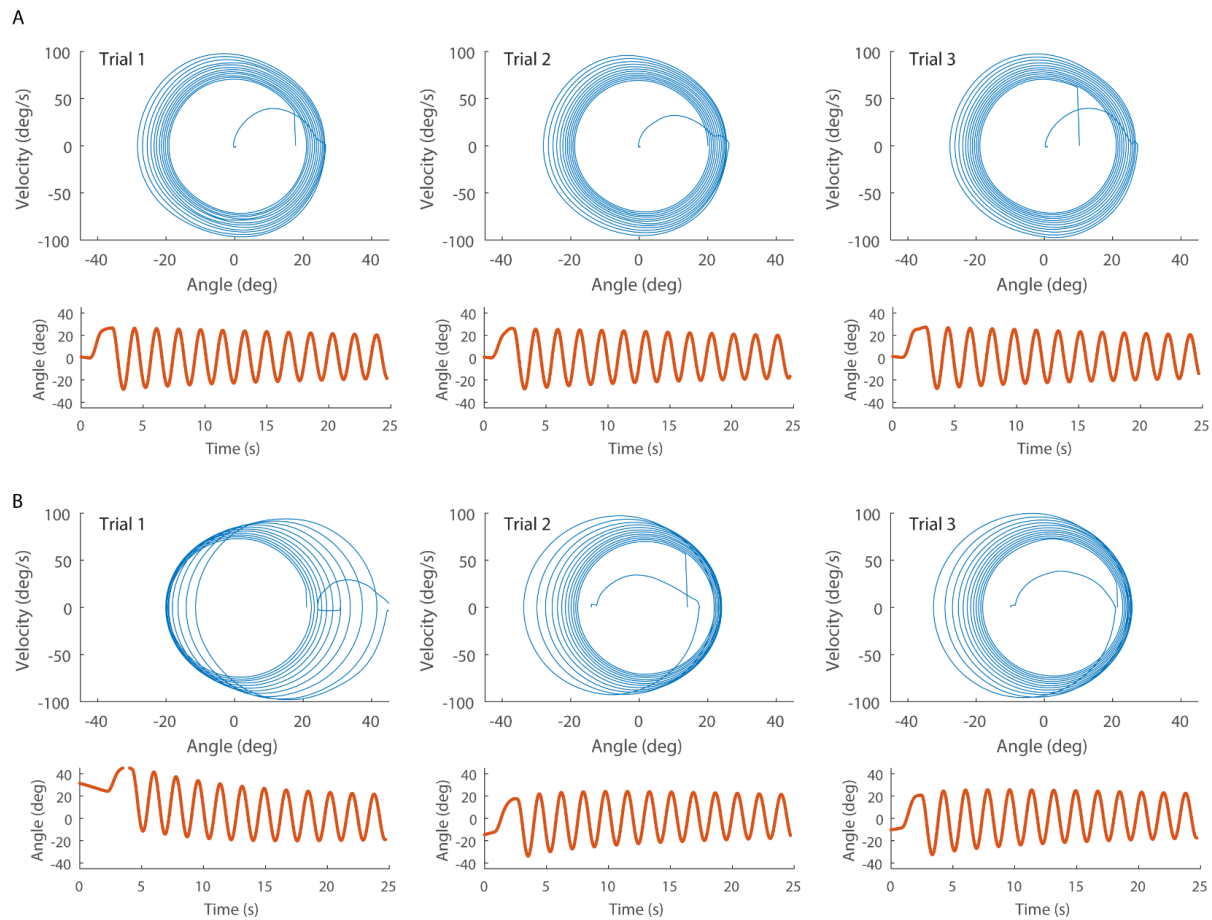
Figure 2. Performance of the AccWalker when running on Android OS 4.4.4 (top panels) vs. running on Android 5.1 (bottom panels). The inset in orange shows the time series of the pendulum angle corresponding to the phase space in the figure—drift is clearly evident in the bottom panels.
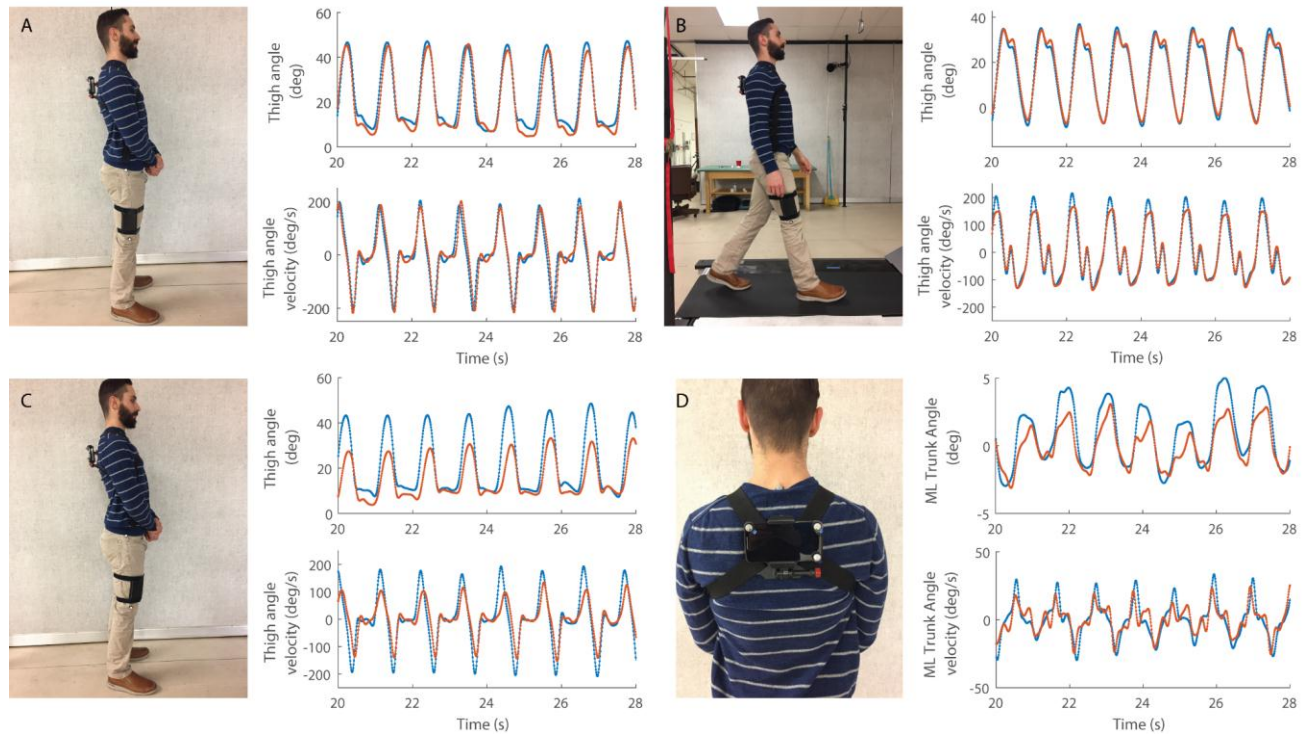
Figure 3. Thigh angle (A) and velocity (B) recorded by the motion capture system (blue) and the AccWalker (orange) during the stepping-in-place task. Greater thigh angle represents greater thigh flexion.
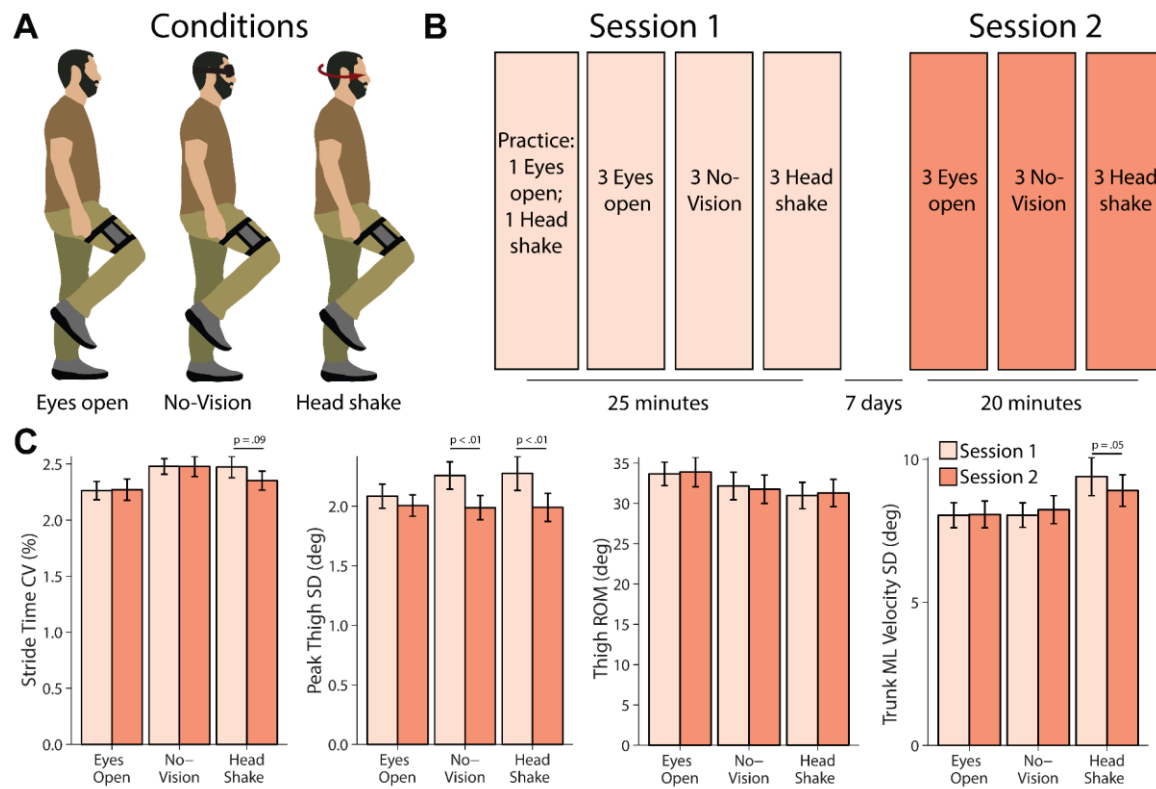
Figure 4. (A) Experimental conditions, (B) study design, (C) changes in the dependent measures for each sensory condition and session.

Table I

Average thigh and trunk metrics calculated from 3D motion capture and AccWalker, and the results of Bland-Altman LOA test when the phone was properly placed on the leg (see Figure 3A).

	Unit	Motion capture		AccWalker		95% LOA				
		Mean	SD	Mean	SD	Bias	SD	Lower	Upper	SD LOA/SD
Temporal metrics										
Timing accuracy	%	-0.67	3.44	-0.69	3.43	-0.02	0.05	-0.13	0.09	1.57%
Mean stride time	s	1.14	0.04	1.14	0.04	0.00	0.00	0.00	0.00	2.53%
CV stride time	%	2.06	0.32	2.07	0.32	0.01	0.07	-0.11	0.15	21.88%
ACF1	a.u.	0.31	0.16	0.30	0.15	-0.01	0.06	-0.13	0.11	37.62%
Pace drift	s	0.04	0.02	0.04	0.02	0.00	0.00	0.00	0.00	4.60%
Spatial metrics										
Peak thigh SD	deg	1.99	0.57	2.11	0.55	0.12	0.08	-0.05	0.28	14.04%
Peak thigh SD/ROM	%	4.55	0.92	4.56	0.91	0.01	0.17	-0.33	0.34	18.13%
Thigh ROM	deg	44.03	8.54	46.63	8.57	2.65	1.36	-0.07	5.37	15.95%
Peak Lift Vel SD	deg/s	11.90	2.95	10.91	2.30	-0.99	1.21	-3.41	1.43	41.05%
Peak Return Vel SD	deg/s	12.23	2.69	13.98	3.63	1.76	1.32	-0.88	4.39	48.98%
Trunk: Spatial metrics										
ML SD	deg	1.41	0.43	1.61	0.50	0.20	0.39	-0.57	0.97	88.78%
ML velocity SD	deg/s	8.24	2.53	9.88	2.57	1.64	1.93	-2.20	5.48	76.44%

Note. SD – standard deviation, Bias – average difference between the 3D motion capture and AccWalker, SD LOA – standard deviation of the difference between the 3D motion capture and AccWalker, SD LOA/SD – ratio of the SD LOA to SD of the 3D motion capture (expressed as percentage).

Table II

Average thigh and trunk metrics calculated from 3D motion capture and AccWalker, and the results of Bland-Altman LOA test when the phone was placed more anteriorly on the leg (see Figure 3C).

	Unit	Motion capture		AccWalker		95% LOA				
		Mean	SD	Mean	SD	Bias	SD	Lower	Upper	SD LOA/SD
Temporal metrics										
Timing accuracy	%	-1.93	3.44	-1.93	3.43	0.00	0.05	-0.10	0.10	1.46%
Mean stride time	s	1.13	0.04	1.13	0.04	0.00	0.00	0.00	0.00	1.46%
CV stride time	%	1.88	0.30	1.98	0.33	0.10	0.13	-0.16	0.37	45.00%
ACF1	a.u.	0.18	0.14	0.11	0.11	-0.07	0.10	-0.26	0.13	70.01%
Pace drift	s	0.02	0.01	0.02	0.01	0.00	0.00	0.00	0.00	10.22%
Spatial metrics										
Peak thigh SD	deg	1.98	0.57	1.91	0.60	-0.08	0.21	-0.50	0.34	36.82%
Peak thigh SD/ROM	%	4.93	1.24	6.78	2.15	1.85	1.40	-0.95	4.64	112.56%
Thigh ROM	deg	40.56	6.85	29.09	7.15	-11.47	4.68	-20.83	-2.11	68.33%
Peak Lift Vel SD	deg/s	12.52	3.19	10.78	2.53	-1.74	1.66	-5.07	1.59	52.18%
Peak Return Vel SD	deg/s	11.31	3.49	11.27	4.48	-0.04	1.44	-2.92	2.83	41.22%

Note. SD – standard deviation, Bias – average difference between the 3D motion capture and AccWalker, SD LOA – standard deviation of the difference between the 3D motion capture and AccWalker, SD LOA/SD – ratio of the SD LOA to SD of the 3D motion capture (expressed as percentage).

Table III

ICC(2,k) and SEM values for each variable and condition.

	Unit	ICC(2,k)			SEM		
		Eyes Open	No-Vision	Head Shake	Eyes Open	No-Vision	Head Shake
Temporal metrics							
Mean stride time	s	0.80*	0.80	0.81	0.02	0.02	0.03
CV stride time	%	0.77	0.82	0.81*	0.34	0.27	0.31
ACF1	a.u.	0.49*	0.78	0.44	0.16	0.10	0.15
Pace drift	s	0.23	0.47	0.54	0.02	0.02	0.02
Spatial metrics							
Peak thigh SD	deg	0.82	0.73*	0.89*	0.32	0.46	0.36
Thigh ROM	deg	0.90	0.92	0.94	4.10	3.82	3.23
Peak Lift Vel SD	deg/s	0.82	0.77*	0.88*	1.39	1.97	1.78
Peak Return Vel SD	deg/s	0.90	0.85*	0.89*	1.64	2.27	2.23
Trunk: Spatial metrics							
ML SD	deg	0.59	0.89	0.94*	0.33	0.17	0.16
ML velocity SD	deg/s	0.64	0.90	0.96*	1.74	0.94	0.86

*Note. * signifies presence of a practice effect.*

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Appendix C

Rhea, C.K., Kuznetsov, N.A., Robins, R.K., Jakiela, J.T., Long, B., Ross, S.E., Wright, W.G., Haran, F.J., Bailie, J.M., Yanagi, M.A., & Duckworth, J.L. Acute, sub-acute, and chronic effects on neuromotor performance after repeated low-level blast exposure. *Military Health System Research Symposium*, Kissimmee, FL, August, 2017, national conference, poster.

Title: Acute, sub-acute, and chronic effects on neuromotor performance after repeated low-level blast exposure

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Background: The full extent of the impact of acute and chronic effects of sub-concussive blast exposure on military personnel health is poorly understood and is an area of research that warrants further exploration. Military personnel routinely near an explosive weapon or device may receive repeated sub-concussive head trauma from low level blasts (LLB), such as special operators, range security officers, breachers, machine gunner, riflemen, infantry, motorman, and anti-tank missilemen. Thus, documenting the acute and chronic effects of LLB exposure is necessary in order to make evidence-based health care decisions for military personnel. Our previous work tested participants enrolled in the Neurocognitive Assessment of Blast Exposure Sequelae in Training (NC-BEST) study and showed that neuromotor performance (i.e., balance) was acutely affected in a negative way for up to three days after LLB exposure. The Neurologic Effects of Training Associated Blast (I-TAB) project has since commenced to examine the acute, sub-acute, and chronic effect of LLB exposure. This abstract reports on the preliminary neuromotor data from I-TAB.

Methods: Active-duty U.S. Navy personnel (N=11) performed a series of tests, including neuromotor assessment, before and at eight time points after (30 min, 6 hours, 24 hours, 72 hours, 2 weeks, 3 months, and 6 months) LLB exposure received during a heavy weapons training program. The neuromotor test had participants step-in-place for 70 seconds with a smartphone running a custom app attached to their thigh. The range of motion (ROM) and standard deviation (SD) of the thigh were measured with the smartphone and examined across time points using a linear mixed model (LMM) analysis.

Results: For ROM, a main effect of time was observed (p>.001), exhibiting a U-shaped function. ROM at baseline was greater than all other post-LLB exposure time points (p<0.05), apart from 6 months. There was a continuous decrease ROM at all time points from 30 min to 72 hours (p<.001).

ROM values began to increase after 72 hours, returning back to baseline levels at 6 months. For SD, a main effect of time was observed (p<.001). Similarly, SD at baseline was greater than all other post-LLB exposure time points (p<0.05) except at 6 months. SD at the 30 mins, 6 hour and 24 hour time points were not different from each other, but dropped again at the 72 hour time point relative to the 30 min time point (p=0.009). SD began to increase at 2 weeks and 3 months compared to 72 hour and retuned to baseline levels at 6 months.

Conclusions: The U-shaped observation shows that participants were moving less (lower ROM) and with less variability (lower SD) after LLB exposure, indicative of a transition toward more robotic and less adaptive neuromotor behavior. This decrement in performance was observed at the acute and sub-acute phases after LLB exposure. In the chronic phase, neuromotor performance returned back to baseline values. This suggests that LLB exposure may have a longer effect on neurological functioning than originally thought, a postulate that will be addressed with appropriate statistical power as I-TAB enrollment reaches maturity.

Disclaimer: The opinions or assertions contained herein are the private ones of the author/speaker and are not to be construed as official or reflecting the views of the Department of Defense, the Uniformed Services University of the Health Sciences or any other agency of the U.S. Government.

Appendix D

Rhea, C.K., Kuznetsov, N.A., Robins, R.K., Jakiela, J.T., LoJacono, C.T., Ross, S.E., MacPherson, R.P., Long, B., Haran, F.J., & Wright, W.G. Dynamic balance decrements last longer than 10 days following a concussion. *International Society of Posture & Gait Research*, Ft. Lauderdale, FL, June 2017, international conference, podium.

Title: Dynamic balance decrements last longer than 10 days following a concussion

Authors: Rhea, C.K., Kuznetsov, N.A., Robins, R.K., Jakiela, J.T., LoJacono, C.T., Ross, S.E., MacPherson, R.P., Long, B., Haran, F.J., & Wright, G.W.

BACKGROUND AND AIM: Mild traumatic brain injury (mTBI), synonymous with concussion, has received considerable public and scientific attention in recent years. Balance decrements (e.g., more variable motion) is a cardinal symptom that is commonly screened for after a concussive event. Most concussion symptoms resolve within 7-10 days after the initial head trauma. However, there is emerging evidence that the effects of a previous concussion may linger longer than previously thought. The purpose of this study was to examine dynamic balance characteristics in participants who received a concussion within the last 40 days compared to a non-concussed population. It was hypothesized that the concussed participants would have more variable motion and a larger range of motion in the objectively measured dynamic balance task.

METHODS: Concussed participants (N=10, 20.1 ± 1.1 yrs, 19.3 ± 11.4 days since the concussion) and non-concussed participants (N=69, 22.1 ± 2.6 yrs) participated in a large, multi-site concussion study. The dynamic balance portion of the study was assessed using a 70-second stepping-in-place task while characteristics of each stride were objectively measured using a custom Android app from a smartphone placed on the participants' thigh. After two practice trials, participants performed the stepping-in-place task in the following conditions three times each: (1) eyes open (EO), (2) eyes closed (EC), and (3) while shaking their head laterally (HS). Dynamic balance characteristics were quantified by examining the temporal variability of stride time [coefficient of variation (CV) of the duration between peak thigh flexion] and range of motion (ROM) of the thigh (difference between the mean thigh angle during the peak extension and flexion phases of the movement). A linear mixed model with group (concussion vs. healthy) and condition (EO, EC, and HS) factors was used, followed up with simple effect comparisons if an interaction effect was significant.

RESULTS: Participants with a concussion (M = 2.95%, SE = .20) showed greater stride time CV than non-concussed participants (M=2.48%, SE = .05) in the EC condition (p <.01). Concussed participants also showed a tendency to use smaller thigh ROM in the EC condition (M = 34.58°, SD = 2.44) compared to non-concussed participants (M = 39.66°, SD = 1.15), p = 0.09.

CONCLUSIONS: The combination of a smaller ROM paired with more variable movement timing suggests altered neuromotor control for the concussed participants, even though they were well outside the window of time where balance symptoms are typically resolved. This suggests that more challenging dynamic balance tasks may be needed to more accurately identify neuromotor dysfunction after head trauma.

Appendix E

Kuznetsov, N.A., Robins, R.K., Jakiela, J.T., LoJacono, C.T., Ross, S.E., MacPherson, R.P., Long, B., Haran, F.J., Wright, W.G, & Rhea, C.K. Convergent validity of metrics provided by a portable gait assessment protocol. *North American Society for the Psychology of Sport and Physical Activity*, San Diego, CA, June 2017, national conference, podium.

Title: Convergent validity of metrics provided by a portable gait assessment protocol

Authors: Kuznetsov, N.A., Robins, R.K., Jakiela, J.T., LoJacono, C.T., Ross, S.E., MacPherson, R.P., Long, B., Haran, F.J., & Wright, W.G & Rhea, C.K.

Detecting changes in neuromotor function after TBI is difficult in field-based settings and requires subjective judgment due to limited access to laboratory equipment. To this end, we have begun designing a sensor-based test protocol utilizing Android phones to measure dynamic balance during a stepping-in-place task as a surrogate of gait. The aim of the current study was to evaluate the convergent validity of our protocol in comparison to Balance Error Scoring System (BESS), Sensory Organization Test (SOT), and Community Balance and Mobility Scale (CB&M) as these tests have been previously used to characterize balance deficits after a concussion. Young adults with self-reported concussion history (N=10 with less than 40 days post-injury and N=7 with more than 12 months post-injury) performed the stepping-in-place task at a prescribed stepping pace in the following conditions: (1) eyes open (EO), (2) eyes closed (EC), and (3) while continuously oscillating their head laterally (HS). Results showed that stride time variability was negatively correlated with the total CB&M score in the EO (rho = -.55, p = .02) and EC (rho = -.61, p < .01) conditions, suggesting that higher temporal variability in keeping the stepping tempo is associated with worse performance on CB&M—a subjective test of dynamic balance designed for high-functioning individuals with brain injury. Greater stride time variability in the EC condition was also associated with greater number of total BESS errors (rho = .58, p = .01) and showed a trend for this relationship in the EO condition (rho = .44, p = .07). There was no correlation between stride time variability and the SOT composite score. These results suggest that stride time variability during stepping in place is most strongly associated with dynamic balance performance such as tested by the CB&M, but also has convergent validity with respect to static tests of balance. The protocol could be used as an additional portable sensor-based assessment of balance function in individuals with suspected mild traumatic brain injury.

Appendix F

Kuznetsov, N.A., Jakiela, J.T., Ross, S.E., & Rhea, C.K. Adaptive fractal analysis of the center-of-pressure during the sensory organization test in individuals with concussion. *Human Movement Science & Biomechanics Research Symposium,* Chapel Hill, NC, March, 2017, regional conference, podium.

ADAPTIVE FRACTAL ANALYSIS OF THE CENTER-OF-PRESSURE DURING THE SENSORY ORGANIZATION TEST IN INDIVIDUALS WITH CONCUSSION

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Introduction: Balance problems can resolve within 3-5 days after sustaining a concussion based on the sensory organization test (SOT) and balance error scoring system (BESS). However, nonlinear dynamics metrics such as Sample Entropy (SampEn) applied to the center-of-pressure (COP) recordings demonstrate that subtle balance control differences can last more than 6 months post-injury in some cases. SampEn however only examines COP variability at a single scale, which is not consistent with the multiple scales of postural control reported in the literature. Adopting an analysis that examines multiple scales of control may help further increase the sensitivity of COP-based measures to identify lingering balance dysfunction after a concussion.

Objective: This study used adaptive fractal analysis (AFA) to evaluate multiple scales of postural control during the SOT in healthy and concussed individuals.

Methods: We used a cross-sectional design with four groups of active young adults: no concussion history (N = 80), acute concussion (N = 6, median = 4 days, range = 3 to 9 days), recent concussion (N = 5, median = 30 days, 16 to 37 days), and long-term history of concussion (N = 7, median = 4 yrs, range = 1 to 14 yrs). Subjects performed all 6 conditions of the SOT for 3 trials each and lasting 20 s per trial. AFA was used to characterize patterns of anterior-posterior (AP) COP variability within two scaling regions: the fast scaling region spanning from 30 to 170 ms and the intermediate region spanning from 0.25 to 2.57 s. Patterns of variability within each region were characterized using the alpha scaling exponent (α): $\alpha =0.5$ signified the presence of random dynamics, $\alpha < 0.5$ signified anti-persistent dynamics, and $\alpha > 0.5$ signified persistent dynamics. Smaller α was interpreted as indicating stronger neuromuscular control.

Results: Acutely concussed individuals showed more persistent AP COP variability in the fast scaling region than controls in SOT conditions 3 (moving visual surround), 4 (moving floor), 5 (moving floor, eyes closed), and 6 (moving floor and visual surround) (all $p<.05$). This difference was not present in the recently concussed and the long-term groups (Figure 1). Acutely concussed individuals had more persistent AP COP dynamics in the intermediate scaling region in SOT condition 3 compared to controls, and this difference was not present for the other concussed groups. The SOT composite score did not detect any differences between the control and acute group ($p>.05$).

Conclusions: These results indicate that the fast scale of COP dynamics (30-170 ms) is more sensitive to the effects of concussion than the intermediate scale of COP dynamics. The results also indicate that balance symptoms of concussion resolve within 9-16 days after the injury.
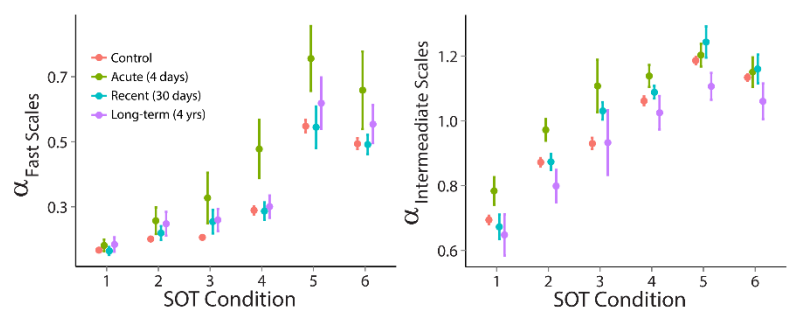

Figure 1. Scaling exponent (α) for the fast and intermediate scales during the SOT. Error bars indicate standard error of the mean.

Appendix G

Kuznetsov, N.A., Robins, R.K., Ross, S.E., Wright, W.G., Haran, F.J., Jakiela, J.T., Bailie, J.M., Yanagi, M.A., Long, B., Duckworth, J.L., & Rhea, C.K. Neuromotor testing post-mTBI: Reliability of movement metrics from a smartphone application. *Military Health System Research Symposium*, Kissimmee, FL, August, 2016, national conference, poster.

Title: Neuromotor testing post-mTBI: Reliability of movement metrics from a smartphone application

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Background: Dynamic stability of walking is compromised in individuals who have sustained a mild traumatic brain injury (mTBI). Detecting changes in neuromotor function via a dynamic stability task after mTBI frequently requires subjective judgment. To this end, we have developed a cost-effective Android-based smartphone application (the AccWalker app) to objectively measure spatiotemporal features during a dynamic stability task, which becomes more variable post-TBI. Our previous work showed that military personnel who were exposed to low-level blasts (LLB) had significantly worse dynamic balance post LLB exposure when assessed with our AccWalker app. We recently developed version 2 of the app (AccWalker v.2) to include visual and vestibular perturbations during the dynamic stability test. This study evaluated the test-retest reliability of the temporal and spatial variability metrics derived from AccWalker v.2 in individuals without mTBI.

Methods: Healthy young adults (N = 29, 13 men and 16 women, 24.8 ± 4.7 yrs) performed a stepping-in-place task in three conditions three times each [eyes open (EO), eyes closed (EC), and lateral head rotation (LHR)] and repeated the testing a week later. Subjects were instructed to step in synchrony to a 1.74 Hz metronome for the first 10 seconds and continue at the same pace for another 60 seconds without the metronome. Temporal variability was calculated using the coefficient of variation (CV) of the stride period (Period CV). Spatial variability was calculated using the standard deviation (SD) of the peak thigh flexion during stepping (Thigh SD). Both metrics were derived from thigh orientation measurement provided by the AccWalker v.2 app using the gyroscope, accelerometer, and magnetometer sensors on the Motorola Moto X2 smartphone (Android OS 4.4.4 Victara). The mean for each testing day was used to estimate test-retest reliability using intraclass correlation coefficient, ICC(2,k) in each condition. ICC values were interpreted as follows: < 0.40 = poor, $0.40 - 0.59$ = fair, $0.60 - 0.74$ = good, ≥ 0.75 = excellent, and ≥ 0.70 = clinically acceptable.

Results: For temporal variability, results showed excellent test-retest reliability for Period CV in all conditions (EO: 0.79; EC: 0.84; LHR: 0.83). The standard error of the mean (SEM) values in the EO, EC, and LHR conditions were 0.34%, 0.26%, and 0.30%, respectively. Mean Period CV in EO, EC, and LHR was 2.27%, 2.49%, and 2.42%, respectively. For spatial variability, results also showed excellent test-retest reliability for Thigh SD (EO: 0.84; EC: 0.74; LHR: 0.79). The SEM values in EO, EC, and LHR were 0.32, 0.44, and 0.45 degrees, respectively. Mean Thigh SD in EO, EC, and LHR were 2.02, 2.06, 2.10 degrees, respectively.

Conclusions: The reliability of temporal and spatial variability in a dynamic stability test measured by AccWalker v.2 all had excellent-to-good test-retest reliability and were clinically acceptable (ICC > .70). These results are especially encouraging for the LHR condition, as this condition perturbs vestibular functioning, which is often deficient following an mTBI. Future research will focus on the clinical utility of this device for identifying military personnel with impaired neuromotor functioning after a suspected mTBI.

Disclaimer: Opinions, interpretations, conclusions and recommendations are those of the authors and do not constitute an endorsed by the Department of Defense, Uniformed Services University, U.S. Army, U.S. Navy, or any other agency of the Federal Government.

Appendix H

Rhea, C.K., Kuznetsov, N.A., Bailie, J.M., Yanagi, M.A., Long, B., Haran, F.J., Ross, S.E., Wright, W.G., Robins, R.K., Jakiela, J.T., Sargent, P.D., & Duckworth, J.L. Concussion history influences neuromotor performance after exposure to repetitive low-level blast exposure. *American Society of Biomechanics*, Raleigh, NC, August 2016, national conference, poster.

CONCUSSION HISTORY INFLUENCES NEUROMOTOR PERFORMANCE AFTER EXPOSURE TO REPETITIVE LOW-LEVEL BLAST EXPOSURE

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INTRODUCTION

Mild traumatic brain injury (mTBI), synonymous with concussion, has received considerable attention within the military, as the number of injuries sustained has increased during recent combat operations [1]. This research has led to military-specific guidelines for clinical healthcare providers in regard to mTBI screening, diagnosis, and injury management [2]. The guidelines require mandatory neurological and functional evaluations that focus on changes in sequelae following a clinically diagnosed mTBI, including subjective symptomology, neurocognitive functioning, and neuromotor functioning (e.g., assessment of gait and/or balance). These guidelines focus on the identification of mTBI following a head trauma event, but very little is known regarding the effects of subclinical head perturbations. The majority of subclinical head perturbations experienced by military members are a result of mechanisms similar to those seen in the sport domain (i.e., blunt-force trauma). However, a number of military personnel are exposed to subclinical head perturbations as a result of blast exposure [3]. It is currently unclear whether the effects of repetitive blast exposure, especially low-level blast (LLB) exposure, experienced by military personnel during their training and operational careers has a cumulative effect. Recent research on this topic shows that chronic and acute LLB exposure may result in changes in symptomology,

neuroimaging outcomes, and neurocognitive functioning [4-6]. However, there is still much to be understood in this space. For example, it is plausible that a population who experienced a previous mTBI may perform differently after LLB exposure due to an increased neurological sensitivity to head trauma.

The purpose of this study was two-fold: (1) to examine neuromotor performance before and after LLB exposure in a military population, and (2) to determine whether a history of mTBI influenced neuromotor performance before or after LLB exposure. It was hypothesized that LLB exposure would lead to more variable neuromotor performance and this alteration would be more pronounced in those with a history of mTBI.

METHODS

Active-duty United States Navy personnel ($N = 90$) performed a stepping-in-place task for 120s prior to repetitive LLB exposure from training (Baseline), and again immediately after (POST-1), 24 hours after (POST-2), and 72-96 hours after the completion of the training (POST-3). The stride period was recorded using a portable sensor and taken as an objective measure of neuromotor functioning (Figure 1).
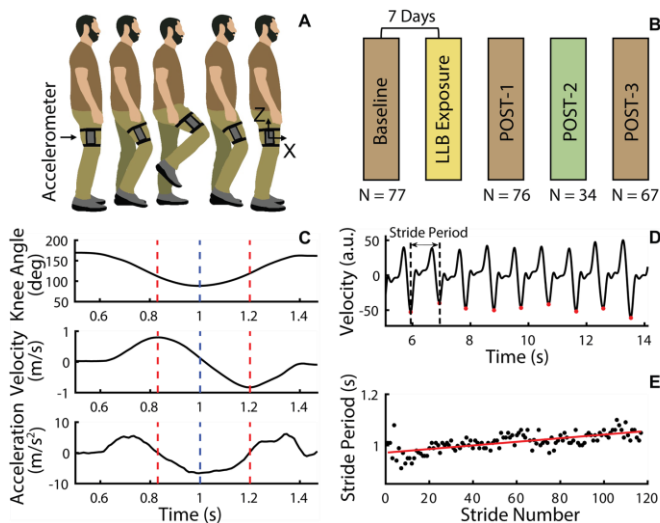
Figure 1: A) stepping-in-place task, B) study design C) relation between the knee angle and the vertical velocity and acceleration recorded by AccWalker app, D) velocity was calculated from acceleration via integration, and E) time series of the stride period as a function of step number within a single 120 s trial.

The variation of the stride period was characterized using lag-1 autocorrelation. A positive value indicates a persistent time series, a negative value indicates an anti-persistent time series, and a value of zero indicates an uncorrelated time series. Participants were also asked to self-report their mTBI history. A linear mixed model was used to compare the lag-1 autocorrelation values across time points and as a function of mTBI history followed by simple contrast comparisons for statistically significant effects.

RESULTS AND DISCUSSION

There were changes in neuromotor functioning immediately after LLB exposure in participants with self-reported previous mTBI ($p = .02$), such that individuals with a self-reported previous mTBI had higher autocorrelation values immediately after LLB exposure as compared to those without a self-reported previous mTBI. This suggests that the neuromotor adaptive ability in the individuals with a concussion history may be compromised. That is, their previous head trauma may have increased their sensitivity to relatively low head perturbations, which may partially account for their change in neuromotor performance after LLB exposure. However, this postulate warrants further investigation and future work should use a clinically

diagnosed concussion rather than self-reported history, as well as considering the mechanism of injury (blast vs. blunt-trauma).
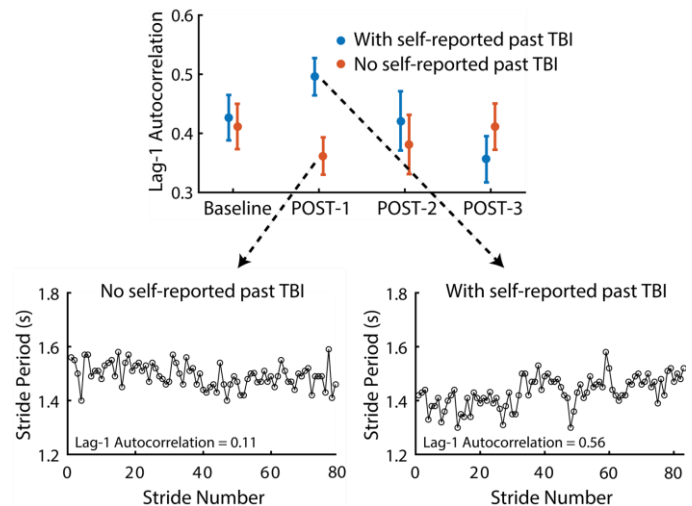

Figure 2: Change in lag-1 autocorrelation as a function of training and previous self-reported concussion history. The error bars depict the standard error of the mean.

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DISCLAIMER
Opinions, interpretations, conclusions and recommendations are those of the authors and do not constitute an endorsement by the Department of Defense, Uniformed Services University, U.S. Army, U.S. Navy, or any other agency of the Federal Government.

Appendix I

Rhea, C.K., Kuznetsov, N.A., Long, B., MacPherson, R.P., Jakiela, J.T., Robins, R.K., Haran, F.J., Ross, S.E., & Wright, W.G. Can a smartphone app be used to objectively measure neuromotor control after a concussion? *North American Society for the Psychology of Sport and Physical Activity*, Montreal, Quebec, June 2016, national conference, podium.

North American Society for the Psychology of Sport and Physical Activity
Conference abstract (2100 character limit, with spaces)
Conference dates: June 15-18, 2016
Location: Montreal, Quebec, Canada

Title: Can a smartphone app be used to objectively measure neuromotor control after a concussion?

Authors: Rhea, C.K., Kuznetsov, N.A., Long, B., MacPherson, R.P., Jakiela, J.T., Robins, R.K., Haran, F.J., Ross, S.E., & Wright, W.G.

Abstract: The development of smartphones over the past decade has allowed researchers to leverage this technology in a variety of ways. One traditional barrier in concussion research was difficulty in objective balance assessment outside the laboratory. While sensitive and specific objective measures have been developed in laboratory environments, field-based and clinical work with patients with a suspected concussion have traditionally relied on subjective balance assessments due to time, financial, and equipment constraints. One potential solution to this barrier is to utilize smartphone technology, which has evolved to include a variety of sensors in an open-access platform in a cost-effective manner. Our research team developed an Android-based smartphone app that collects objective neuromotor data in a dynamic balance test outside the laboratory. Using accelerometer, gyroscope, and magnetometer sensors embedded in an Android-based phone, this presentation will show how neuromotor data can be collected and the potential clinical utility of our smartphone app in concussion research. The Android-based phone sensors were used to detect device orientation from the Motorola X2 (Motorola Mobility, Chicago, IL) and have shown high validity relative to a commercially available inertial measurement unit (XSens, Enschede, Netherlands) and to a motion capture system (Qualisys, Göteborg, Sweden), Pearson's $r > .99$ for both systems. When paired with a stepping-in-place task, our app has also shown adequate between-day reliability and very high within-day reliability (between-day Pearson $r = 0.73$ and within-day $r = 0.93$). The clinical utility of our innovation is the potential ability to measure neuromotor control after a concussion in an objective manner, which can then be compared to normative data embedded within the phone. The final product will be an Android-based smartphone app that will inform the end-user about the dynamic balance ability of their patient relative to a non-concussed population, which could be used within a suite of tests to screen for a concussion.

Appendix J

Kuznetsov, N. A., Cone, B., Schleich, K.N., Hege, M.A., Ross, S.E., Long, B., Robins, R.K., Wright, W.G., Haran, F.J. & Rhea, C.K. Reliability of movement timing metrics provided by a portable gait assessment protocol. *North American Society for the Psychology of Sport and Physical Activity*, Montreal, Quebec, June 2016, national conference, podium.

North American Society for the Psychology of Sport and Physical Activity
Conference abstract (2100 character limit, with spaces)
Conference dates: June 15-18, 2016
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Title: Reliability of movement timing metrics provided by a portable gait assessment protocol

Authors: Kuznetsov, N. A., Cone, B., Schleich, K.N., Hege, M.A., Ross, S.E., Long, B., Robins, R.K., Wright, W.G., Haran, F.J. & Rhea, C.K.

Dynamic stability of walking is compromised in individuals who have sustained a traumatic brain injury (TBI). Detecting changes in neuromotor function after TBI is difficult in field-based settings and frequently requires subjective judgment due to limited access to laboratory equipment. To this end, we have begun designing a cost-effective Android-based smartphone application (the AccWalker app) to measure dynamic balance activity using a stepping in place task as a surrogate of gait. The aims of the current study were to evaluate the reliability of the AccWalker testing protocol in non-concussed individuals in terms of test-retest reliability (intraclass correlation coefficient; ICC) and absolute reliability (standard error of measurement; SEM). Healthy young adults (N = 48, M = 22.02 yrs, SD = 3.14; 25 men) were instructed to step in place for 120 seconds at a comfortable pace over 6 trials (3 sessions separated by 4 days on average, 2 trials per session). The mean stride period and the coefficient of variation (CV) were calculated for each trial from the vertical acceleration of the thigh recorded by the AccWalker installed on an HTC Desire 510. Results showed that the stride period was greater in session 1 compared to the following sessions, indicating a practice effect. Accordingly, the data from session 1 were not used in the reliability calculations. The two trials within session 2 and session 3 were averaged and an ICC(2,k) was used to calculate test-retest reliability. The results showed excellent test-retest reliability for stride period (ICC = 0.89) and adequate test-retest reliability for stride period CV (ICC = 0.70). The SEM values for both measures were 0.05 s and 0.46%. These results suggest that the temporal metrics obtained with the AccWalker app have adequate test-retest reliability when averages of two trials are used. These results will inform the development of the next version of the AccWalker protocol, with the goal to screen for significant deviations in the spatio-temporal parameters of gait in individuals after TBI.